On Microwave Radio Scintillation Effects and Space Weather Impacts on Electric Power Supply Systems in Middle Latitudes

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In this paper results of morphological studies and investigations on revealing of main characteristics of ionospheric scintillation effects experienced for microwave radio signals for the Space-Earth path, its impacts on navigation and communication systems, dependence on the solar and geomagnetic activity, geophysical and other processes/factors are briefly provided to help system designers who are involved in the activities related to the development and functioning of systems, particularly, for consumers in middle geographical latitudes. Ionospheric propagation model computer code was applied for studying of scintillation effects on microwave radio signals used in the area of Azerbaijan for worst case scenario of main space weather and ionosphere parameters. Part of main results of the complex investigations on possible impact of geomagnetic disturbances of various strengths on electric power supply systems in middle latitudes is described. Daily data on power failures and breakdowns that occurred in Baku capital city (Azerbaijan) and surrounded big urban area in years of descending phase of solar 11-year activity cycle was investigated and analyzed.

1. Introduction

Earth's space environment and the Earth itself are subject to influence of space weather [1]. Space weather is determined by the most varied interactions between the Sun and interplanetary space, and the Earth. Ionospheric effects at equatorial, auroral and middle latitudes constitute a second (after magnetospheric storms) major category of space weather effects: electric fields and particles couple the lower atmosphere and ionosphere to the disturbed magnetosphere above, and large-scale changes in total electron content and ionospheric scintillations can adversely affect communications and navigation systems [2, 3].

Results of morphological studies and investigations of main characteristics of ionospheric scintillation effects experienced for microwave radio signals for the Space-Earth path in middle geographical latitude locations, its possible impacts on navigation and communication systems, dependence on the solar and geophysical activity, geophysical and other processes/factors are briefly provided in this paper. Ionospheric propagation model taking into account changes of heliogeophysical conditions were applied for studying of scintillation effects on GHz frequency radio signals used in the Azerbaijan and regional area for worst case space weather scenario.

Solar-activity-induced disturbances produce detrimental changes across long conductors on the Earth, including pipelines, power and telecommunication lines, railways, glass-fiber systems and other systems [4, 5]. Electrical power grids continue become more complex and interconnected, with the result that they have become more vulnerable to solar activity effects that disturb current systems in the ionosphere.

The variable electrojet currents in space (ionosphere) induce secondary voltages and related currents – geomagnetically induced currents (GIC) – at ground level. The GIC may have adverse effects on extended conducting structures at ground like high-voltage power grids and transmission lines, oil and gas pipelines, signal lines, etc. These effects are particularly strong in Northern Europe and Russia, Canada, USA [6], but there are signs that depending on the state of space weather disturbances, they can have disruptive and other adverse effects for power grids located in middle and even low geographical latitudes [7-15].

In this paper we have investigated a possible influence of space weather changes on the operational reliability of the power grids - electric energy supply and transmission systems of Baku capital city with millions of consumers and Absheron Peninsula area (Azerbaijan, middle latitudes).

2. Ionospheric scintillation at Giga-Hertz frequencies and its dependence on heliogeophysical and geographical conditions

Scintillation of a radio signal is a relatively rapid random fluctuation of the signal about a mean level, which is either constant or changing much more slowly than the scintillations themselves. Scintillation can be a phase or an amplitude fluctuation. The ionosphere is the primary source of amplitude and phase fluctuations for VHF, UHF and L-band radio waves. Satellite-to-ground transionospheric radio signal propagation links are affected by electron density irregularities (due to scattering) that can degrade received signal strength; radio signal experiences fading and enhancement of amplitude and phase fluctuations and angle of arrival variations which vary widely with physical, geographical, geophysical and solar effects (frequency, solar and geomagnetic activities, season, location/latitude and time of day) [16, 17].

Communication, navigation, geo-location, surveillance and radar systems often rely on predictions and measurements of ionospheric propagation conditions at any latitudes. Appleton equatorial anomaly (two belts of enhanced electron density ~ ±15^0 away from the magnetic equator) and high (auroral) latitudes are worst sources of scintillation. Meanwhile depending on the space weather conditions (disturbances) scintillation effects can play degradation role in radio wave prorogation in low and even middle latitudes [18-20]. Therefore we have attempted to study morphology and main characteristics of microwave radio waves used in middle latitudes (± 20^0-60^0 of the geomagnetic equator) for communication and navigation purposes, namely GPS signals and those of with higher frequencies (up to 6 GHz).

Morphological studies conducted as a part of UN - ESA research fellow program on the base of available database have qualitatively revealed that 1 - 6 GHz (covering some parts of ultra high and super high frequencies which are affected by ionospheric irregularities) ionospheric scintillation characteristics and its correlations with heliogeophysical conditions as well as the regular and seasonal variations of scintillation activity could be briefly characterized as followings:

2.1. Sunspot number (SSN) dependence

- There was no significant correlation between individual scintillation event occurrences and daily SSN;
- Strong correlation was found between the amplitude of the scintillation and the monthly SSN;
- Correlation between annual scintillation occurrence and the annual SSN was quite strong;
- Annual scintillation activity shows high correlation with solar 11-year activity cycle;
- Scintillation and its disturbance effects are most significant during 3-4 years around the peak solar activity cycle, when SSN ≥ 80. The intensity of ionospheric scintillation can be extraordinarily severe at the solar maximum ("active") years;
- Ionospheric scintillation effects can almost disappear at GHz frequencies in comparatively "quiet" years, when SSN ≤ 30.

2.2. Temporal and geographical dependence

- There are significant seasonal maxima associated with the equinoxes. Peak annual scintillation activity occurs at or just after the equinox periods of year. For example, for equatorial GHz scintillation, peak activity around vernal equinox and high activity at the autumnal equinox have been observed;
- Daily scintillation activity shows peak approximately one hour after sunset at the ionospheric height;
- GHz ionospheric scintillation of any significant amplitude only occurs within approximately ± 30^0 of the magnetic equator for the geostationary communication satellite links;
- GPS L1-band (1.57542 GHz) scintillation observations during the period of high solar activity have showed that scintillation intensities maximize in the Appleton equatorial anomaly region rather than near the geomagnetic equator. This anomaly has considerably higher electron density (N) values in high SSN years than in years of low solar activity. The occurrence of maximum N for anomaly latitudes is near sunset in the years of high SSN, and in the afternoon in years of low solar activity. Thus the post sunset irregularity patches form high electron density fluctuation (ΔN) levels in the years of high solar activity;
- For the polar region, scintillation should not be a problem in the years of solar minimum. Both the auroral and polar regions may be of importance when intense geomagnetic storms occur even during periods of low solar flux;
- Total electron content (TEC) and irregularity slab thickness in the ionosphere also follow the sunspot cycle [19, 21, 22]. Morphological and experimental studies show that the electron (or Faraday) content Ne varies approximately linearly with the 12-month running average SSN ($\Re$) as: $Ne=c_1(1+c_2\Re)$, where both c_1 and c_2 vary diurnally, c_2 is about 0.1 (night) and about 0.2 (day); the TEC is about $5\cdot10^{16}$ elec/m^2 (or 5 TECU) at night at low SSN and about $3\cdot10^{17}$ elec/m^2 (or 30 TECU) during the day at $\Re$ = 100. The irregularity slab thickness varies with $\Re$ as: $\tau=c_3(1+c_4\cdot\Re)$, where $c_3=2.7\cdot10^5$ m (summer), $2.4\cdot10^5$ m (equinox), $2.1\cdot10^5$ m (winter) and $c_4=5\cdot10^{-3}$.
- Over an 11-year solar cycle, the monthly average daytime TEC correlates well with the monthly average solar radio flux, but TEC variations for individual days during most months, do not correlate well with day-to-day changes in solar 10.7-cm radio flux. The solar flare X-rays cause sudden increases in TEC.

Results of studies of major characteristics and dependences of ionospheric scintillations at middle latitudes are summarized as the followings:

2.3. Cause of the scintillation

The daytime random scintillations occur because of the sporadic E_S-layer (particularly, the E_{SC}). The nighttime random scintillations are caused by the spread F-region of the ionosphere. The quasi-periodic scintillations originate from traveling ionospheric disturbances (TID) mainly in the F-region or from sporadic-E disturbances.

2.4. Pattern of scintillation

Scintillation activity level is generally very quiet to moderately active. The probability of occurrence of scintillations as well as their intensity is very low at middle latitudes. Ionospheric scintillation does not represent a serious problem for the navigation and communication at these latitudes, especially in the years of low solar activity.

2.5. At what time of day they occur

The occurrence of random scintillations peaks in summer, between 20.00 LT and 24.00 LT. In other seasons, instead, they occur between 24.00 LT and 04.00 LT. They are observed rarely also during daytime, between 08.00 LT – 09.00 LT and 15.00 LT – 16.00 LT, according to the phase of solar activity cycle. Quasi-periodic scintillations occur between 22.00 LT and 02.00 LT. They were observed also between 08.00 LT and 10.00 LT, during the minimum of solar activity.

2.6. In which periods of the year they occur

Random scintillations occur mainly in the summer and seldom during the other seasons. Quasi-periodic scintillations occur mainly in simmer.

2.7. Frequency dependence of scintillation

The percentage of occurrence (the number of the observed events) decreases with the frequency of transmitted signal. Usually, the observed dependence of scintillation index (S_4) for weak and moderate scintillation is: $S_4 = \alpha \cdot f^{-n}$, where α is the proportionality factor, *f* is the frequency while *n*=1.38 (nighttime) or *n* =1.52 (daytime). The “root-mean-square” (“*rms*”) fluctuation of phase depends on frequency as: $\phi_{rms} = \beta \cdot f^{-1}$, where β is the proportionality factor.

2.8. Solar and geomagnetic activity dependence of the scintillation

In general, the probability of scintillation’s occurrence increases with solar activity. The measurements made until now show that scintillation activity is directly proportional to solar activity, but is generally independent on the planetary geomagnetic index K_P. The severity (and its intensity) of the ionospheric scintillation varies with solar 11-year activity cycle along with other factors. Disturbance effects due to the ionospheric scintillation are most significant near solar maximum period, especially in the high- and low-latitude areas. In years of high solar flux, transionospheric propagation through polar and equatorial regions has experienced deep fading at frequencies ranging from 54 MHz to 4 GHz [19]. The Appleton equatorial anomaly region is the worst source of scintillation where during sunspot maximum years, the fades exceeding peak-to-peak 27-30 dB at GPS L1-frequency are often registered after sunset while only 5-6 dB fades occur within a few degrees of the magnetic equator. Statistics of polar scintillation at solar maximum period show much lower values of occurrence of strong fading than at the equatorial anomaly region.

Although scintillation at middle latitudes is generally not as intense as at equatorial and high-latitudes, weak to moderate levels of scintillation occur. Some cases of severe scintillation have been recorded in middle latitudes. During a magnetic storm on March 22, 1979, peak-to-peak scintillation of 18, 10, 15 and 3.5 dB were recorded at frequencies 136 MHz, and 1.7, 4, and 12 GHz, respectively, on different paths in and around Japan [16, 18].

Irregularity structures can cause scintillation simultaneously on several satellites during magnetically quiet nights. On magnetically disturbed nights (K_P >7) nearly all satellites can be affected at varying levels, most of the night. The near solar minimum observations showed that long periods of scintillation occur under both magnetically quiet and disturbed conditions [19].

The computer code, based on Global ionospheric propagation model, has been modified for taking into account changes of heliogeophysical conditions [19]. It has been used to study the scintillation effects on the navigation and communication signals for sites in European Civil Aviation Conference (ECAC) area and for the Republic of Azerbaijan and near region for GPS signal frequencies. We have chosen worst-case scenario of ionospheric and heliogeophysical conditions: solar radio flux F10.7=100 Jansky, elevation angle i = 10^0, irregularity scale size L = 500 m, irregularity drift velocity v=50 m/s, slope n=3, electron density fluctuation $\Delta N/N$=0.2, local time 23.00.

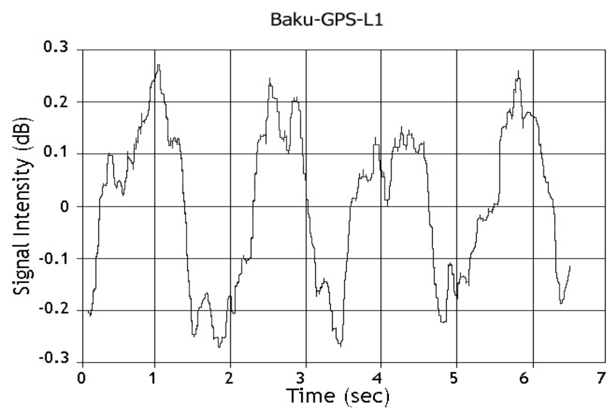

Fig.1. GPS L1 (f=157542MHz) signal scintillation sample for worst case scenario, Baku location.

Results of the application have been detailed (duration of fades, amplitude and phase spectrum of received signal, channel availability, probability of received signal, cumulative probability of fade level, electron density); the figures are not provided in this paper due to the limited space. Results differ, particularly, for different latitudes. It is revealed that although scintillation at middle latitudes is generally not as intense as at equatorial (and high) latitudes, weak to moderate levels of scintillation occur (S_4=0.033) (Fig.1). We have compared results of application for different sites. For Canary Islands (equatorial region), this scenario showed 30-35 dB peak-to-peak fluctuations, while they were not so significant for Baku (middle latitudes) (Fig.1).

3. Impacts of space weather disturbances on the electric power transmission and supply systems in Azerbaijan

3.1. Material and methods

GICs, caused by space weather disturbances, can produce extra magnetic flux saturating the transformer core and leading to transformer heating, increased power demand, alternating current harmonic generation, resulting in interference with power system operation [2].

Geomagnetic disturbance effects on power transmission systems are well studied for high latitude locations where these impacts are very high [6]. But depending on the space weather disturbance levels, these factors can have significant negative influence on middle latitude ground-based power transmission systems [7, 8]. In [11, 14, 15] we have investigated geomagnetic storm effects on Azerbaijani power supply system on the base of daily data on power system behavior within 1994-2005 (data from “Azerenerji” JSC).

This paper examines possible relationship between space weather effects (particularly, the geomagnetic disturbances and solar wind disturbances) and electrical power system behavior in the descending phase of the solar cycle 23 that were probably responsible for the significant power system failures and other disorders. We studied how these geomagnetic effects influenced power supply system operation. Part of main results of this study is briefly provided in this paper.

Daily continuous digital and graphical data on failures and power distribution system behavior in years 2002-2005 as well as part of 2006 created by “Barmek-Azerbaijan” Electricity Network Ltd in grand Baku area (including the Absheron Peninsula) as a part of collaborative study, was deeply investigated. Used methodic and some relevant details of study could be found in [11]. Spectral (Fourier), correlation and cross-correlation analyses were performed with the help of the software STATISTICA, version 6 (StatSoft Inc., 2001) and SPSS, version 12.0 (SPSS Inc., 2003).

3.2. Results and discussions

Alongside with evident rise of power failures during days with increased geomagnetic activity and their dependence on geophysical and technical parameters, there were found some periodicities. After “cleaning”, as much as possible, the available data from such subjective factors as seasonal and societal-economical influences, pure technical kind of effects, etc., the spectral analysis revealed in the remained data quasi-annual (343d), quasi-biannual (686d), quasi-weekly, 60-days, 3-months and other periodicities (in total eight main so called modes with high-level probability among others). We have considered whole data and those of separated as total failures, with known technical-physical reasons and the rest part.

Applied cross spectral analysis (power failures and geomagnetic Ap-index) shows that quasi-biannual periodicity is well pronounced for data cleaned from technical reasons and thought to be affected by space weather disturbances while quasi-annual periodicity is more clearly displayed for total failures.

Two statistically significant and major periodicities found in analyses of total failures by the help of parametrical (Pearson) and non-parametrical (Kendell and Spearman) methods of correlation analyses. They have significant correlation coefficients: 1) 343 days (Fig.2): Kendell’s coefficient r=0.2619 and Spearman’s coefficient r=0.3775 with probability of p=0.000001 in both cases while r=0.3224 and p<<0.000001 for Pearson. It should be noted that this periodicity was dominant in cross spectral analyses for solar wind speed and sunspot number; 2) 686 days (Fig.3): r=0.1142 (Kendell) and r=0.1675 (Spearman) with p=0.000001 for both cases and r=0.1424 (Pearson) when p<<0.000001. This periodicity was significant in cross spectral analyses for failures with geomagnetic Dst and Ap-indices.

Data with failures thought to be affected by space weather changes revealed quasi-annual periodicity as major one with following correlation coefficients: r=0.1489 (Pearson, p<<0.000001), r=0.1203 (Kendell, p=0.000001) and r=0.1562 (Spearman, p=0.000001). Quasi-1.3-year periodicity was found at cross spectral analysis of failures with Dst-index.

Obtained results could be explained by possible influence of space weather disturbances, particularly, by variations in solar, geomagnetic and cosmic ray activities. In general, obtained results show significant interrelationship of power failures with major geomagnetic indices (Figs.2 and 3).

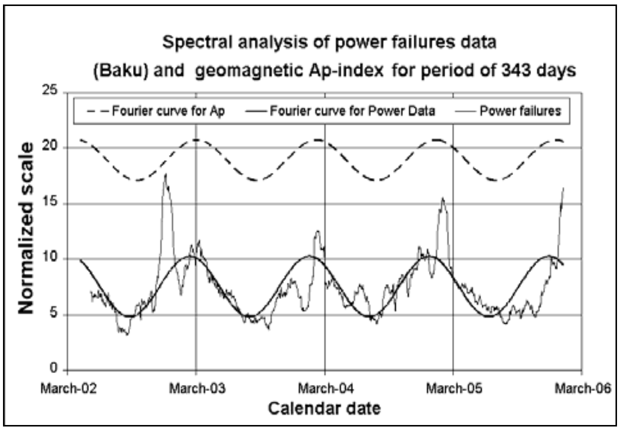

Fig.2. Spectral analyses of power supply system failures and Ap index for period of 343 days, Baku data.

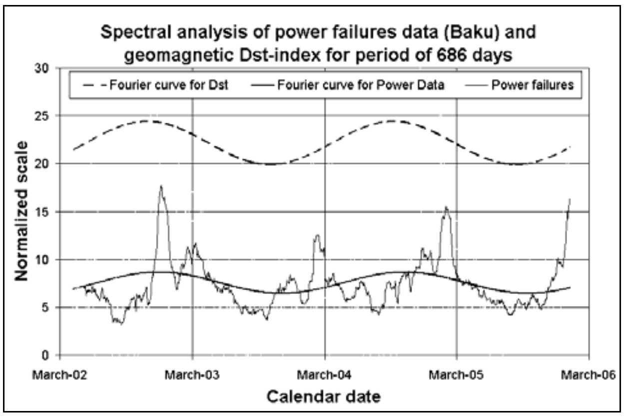

Fig.3. Spectral analyses of power supply system failures and Dst index for period of 686 days, Baku data.

Variability in the geomagnetic activity has several sources which include the variability in the Sun itself that is reflected in the solar wind/interplanetary magnetic field, the annual variability, as well as semi-annual and recurrent variations [23].

The 154 d, 180 d, 1 y and 1.3 y periods are the prominent periods in the mid-term level [24, 25]. The annual period is associated with the excursion of Earth in the heliolatitude known as the "Rosenberg-Coleman Effect" [26]. Due to the $7^0.2$ tilt of the solar rotation axis with respect to the normal of ecliptic, the Earth reaches the highest northern and southern heliographic latitude on September 6 and March 5, respectively. Since the solar wind velocity increases with heliographic latitude, the solar wind velocity exhibit maximum around September 6 and March 5. The annual variation in the ecliptic IMF components Bx and By are due to this dominant polarity regions observed by the Earth due to its excursion to higher heliolatitudes. Bolton [27] reported one year variation in solar wind velocity and ion density.

A slightly longer periodicity of about 1.7 y was observed in cosmic rays during cycle 21 by Valdes-Galicia et al [28]. This period has been identified in solar wind speed, north-south component of IMF and geomagnetic activity [29 - 31].

Periods of 22.6, 6.9, 3.9, 1.97, 1.61, 1.48 and 1.039 years were found in the lower frequency part of the power spectrum of variations of the mean magnetic field (MMF) of the Sun for 1968-2000 [32]. The solar wind observations have revealed 1.3-year periodicity in the Sun, and as any variability in the solar wind, it is reflected in the geomagnetic activity [33, 34]. The 1.3-1.4-year variability originating from the Sun has been observed in the geomagnetic or auroral data [35, 36].

4. Conclusions

It is revealed that the middle latitude scintillation activity is not as intense as that encountered at equatorial or low, auroral or polar latitudes. For the system designers and engineers, however, scintillation activity may reach levels, primarily at VHF and UHF, particularly at L-band and, during solar activity maximum years, which will increase error rates of systems with low fade margins. It is actual problem, particularly, for GPS receivers in middle latitudes which record L-band transmissions from the constellation of GPS or GLONASS satellites around the Earth to provide electron density profiles and L-band scintillations.

Morphological studies have also qualitatively revealed the regular and seasonal variations of scintillation activity and their dependence on heliogeophysical parameters. Scintillation is high in solar maximum years. Geomagnetic activity dependence is not strong. There are significant seasonal maxima associated with the equinoxes.

Scintillation statistics are necessary for experimental planning and in design of signal processing procedures. Knowledge of scintillation and geomagnetic disturbances' effects in advance will help L-band signal users/planners and power operators to differentiate between fluctuations produced by space weather changes (ionospheric irregularities, magnetic storms, so on) and those of equipment or man-made origin.

Analyses of power failures data and relevant space weather parameters have shown that space weather changes can play a significant role in ground-based power system behavior in middle latitudes depending on the heliogeophysical conditions.

Comparison of obtained results and above-mentioned periodicities found in power failures data as well as changes of space weather parameters allow to conclude that geomagnetic activity and solar wind variations affect the sustainable functioning of power supply system.

Probably rapid changes in convection electrojet caused by the flow of energy from the solar wind or magnetospheric shocks associated with storm sudden commencement (having even small magnitude) and changing the geoelectric field could be considered as a disturbance source of these effects.

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