

Impact of Space Weather on Ionospheric Scintillation

Shepeliev V.¹, Lytvynenko O.²

¹Institute of Radio Astronomy NAS, Kharkiv, Ukraine

²Observatory URAN-4, Institute of Radio Astronomy NAS, Odesa, Ukraine

E-mail: shep@rian.kharkov.ua

Abstract.

Amplitude and phase fluctuations of a field of an incident electromagnetic wave arise when the radiation passes through a plasma layer with electron density inhomogeneities. This phenomenon is found in interstellar medium, interplanetary plasma and in the Earth's ionosphere when radio astronomy observations are carried out. Such amplitude and phase scintillation significantly impact on radio astronomy studies at low frequencies and should be taken into account during the observations and data reduction. Ionospheric scintillation affects an accuracy of radio astronomy observations the most severely. On the other hand, observational data distorted by the scintillation provide information on parameters of the scattering medium itself. We observed powerful radio sources with the URAN decameter interferometer network to study a temporal and spatial variation of the ionospheric scintillation in order to determine their relationship with terrestrial phenomena and space weather. We found, that an increase of the ionospheric scintillation measured by the UTR-2 radio telescope coincide with disturbances in the solar wind detected by space laboratories in Earth's orbit and with the URAN interferometers

Introduction

The Sun, as the most powerful source of energy in the solar system, has a decisive effect on many processes in near-earth space and on the Earth. This influence occurs both through electromagnetic radiation in various wavelength ranges and through flux of solar wind particles and coronal mass ejections. At present, within a framework of solar-terrestrial relations, various aspects of this influence are widely studied - from various physical phenomena in the interplanetary medium, magnetosphere and atmosphere of the Earth to the effect on wildlife and technical systems. The influence of the solar activity on radio communication is well known, from the longest wavelengths which do not pass beyond the ionosphere to the shortest ones used in satellite broadcasting and navigation. Radio astronomy observations are also a subject of this influence. Signals from radio sources, received by ground-based radio telescopes, pass through the space plasma and the Earth's ionosphere. Various physical phenomena in this medium lead to absorption of radio emission, scattering, phase and amplitude fluctuations of the received signals, refraction, a dispersion delay, and a polarization plane rotation. All these effects are developed the stronger, the lower frequency of radiation. The influence of the sporadic activity of the Sun often leads to a rather rapid change in parameters of the signal propagation medium, that must be taken into account when radio astronomy studies are planing and conducting.

In the Institute of Radio Astronomy of the NAS of Ukraine, cosmic radio sources are being studied using the world largest UTR-2 radio telescope and smaller URAN instruments, that operate according to various observational programs both independently and as a part of an interferometer network with the maximum resolving power of the order of an arc second [Konovalenko A. et al. 2016]. These studies are carried out in the decameter range, i.e. at the longest wavelengths applicable for the observations from the Earth's surface, which significantly interact with the plasma. Of the mentioned above plasma phenomena, the scattering of radio waves by inhomogeneities of an electron density of the ionized medium

affects the radio astronomical observations at decameter waves the most significantly. It leads to scintillations effect i.e. fluctuations in an amplitude and phase of the received signals.

Scintillation modes in the space plasma

On the way to the observer, radio waves from space radio sources pass through the inhomogeneous plasma of the interstellar medium, the solar wind, and the ionosphere, which have significantly different properties. The interstellar medium is very rarefied, but it has a huge extent and the scintillations at the decameter waves are in the strong scattering regime. In this mode, the emission of a radio source is spread in an angle of scattering, that is the interstellar scintillation leads to an increase in the angular size of a point source proportional to density and extent of the turbulent medium. In particular, the observed angular size of extragalactic radio sources depends on a proximity of a line of sight to the Galaxy plane and can be approximated by the empirical relation [Shishov et al., 2001]:

$$\theta_s \cong 20(10\lambda)^{2.2}(\sin b)^{-0.6},$$

where b is a galactic latitude, λ is in meters, and θ_s is in microseconds of arc. At the frequency of 25 MHz even for $b = 90^\circ$ this expression gives an estimate $\theta_s \approx 0,75''$ i.e. of the order of maximum angular resolution of the URAN interferometer network and therefore the scattering must be taken into account on the lines of sight close to the galaxy plane when determining an image of a radio source.

The interplanetary medium is significantly less extended but denser than the interstellar one. Scattering in it depends on the proximity of the line of sight to the Sun. At small elongations scattering can be strong up to the decimeter wavelengths [Anantharamaiah et al., 1989], and at the decameter wavelengths strong scintillation and distortion of a source image is observed up to elongations 90° . This effect limits the period of interferometer observations of compact radio sources in this range to night time. At larger elongations, scintillation is weak and, due to the high speed of the solar wind, a scintillation period is of the order of one second. In this case, the amplitude flickers are well averaged and have weak effect on an accuracy of source flux measurements. However, phase fluctuations at an interferometer output expand a signal spectrum and can limit coherent integration time and so a sensitivity of the instrument. In addition, unlike the interstellar medium, the turbulence in the interplanetary plasma is affected by the space weather and does not remain constant over time. For example, when a coronal mass ejection propagates through the interplanetary medium, the interplanetary scintillation index increases significantly [Kalinichenko et al., 2013, Glyantsev et al., 2015]. Such an increase in turbulence of the interplanetary medium lasting up to several days caused by the sporadic solar activity also increases the signal bandwidth at the correlator output, that limits a possibility of interferometer observations with high sensitivity [Shepeliev et al., 2020]. An account of solar activity events must be used for a short-term forecast when determining the strategy of highly sensitive observations.

The third layer of the plasma on the path of radio waves to a radio telescope is the Earth's ionosphere – the least extended but most dense medium. This layer introduces the greatest distortion in the received signal at the decameter wavelengths. The scintillation on ionospheric irregularities is often high in amplitude, and its period is comparable to the transit time of the source through a radio telescope pattern. It makes difficult to obtain a reliable estimate of the received signal power. Therefore, a prediction of the scintillation level raising, and hence an analysis of its causes, is important for the decameter radio astronomy. The level of ionospheric scintillation depends on the time of day and season. Observations with the URAN and the UTR-2 show that the average level of the ionospheric scintillation is quite high in the summer time. Therefore, for the observations at the decameter wavelengths, winter time is mainly used, when the scintillation index in nighttime observations is in the range of 0.1–0.5 both in the period of

minimum and maximum of the solar activity. This value makes it possible to obtain sufficiently high-quality radio astronomy data. However, sometimes there are periods of several days with an ionospheric scintillation index $SI \sim 1$, when it is practically impossible to obtain reliable data.

Data reduction and results

To investigate the causes of such events, we used archived data of cosmic radio sources observations with the URAN interferometers. These data have been processed to obtain the ionospheric scintillation indexes. There are no long periods of continuous observations in this data set. As a rule, one session of the interferometer observations lasts one week and is repeated a month later. We selected the sessions during which there was a sharp increase in the scintillation index relative to its ordinary level. In this work, we study possible connection of such events with the space weather. Therefore, for the selected sessions, the level of solar wind turbulence was also determined by the method proposed in [Shepeliev et al., 2020]. In that work, it was shown that a width of a spectrum of ionospheric scintillations at the output of the URAN interferometer, measured in observations of extended radio sources, does not exceed 0.1 Hz. Consequently, for a compact radio source flickering both on the ionospheric irregularities and on the interplanetary ones, it is possible to filter a part of the spectrum larger than this value, which is determined only by the interplanetary scintillations. It was shown that an increase in the energy of the high-frequency part of the spectrum correlates with an increase in the turbulence of the interplanetary medium during abrupt changes in the solar wind parameters measured in the Earth's orbit and associated with manifestations of a sporadic solar activity. In this work, we used the compact source in the Crab Nebula, which was observed in every session, as a probe for determining the level of the solar wind turbulence. The part of the spectrum of the interferometric signal of the same source lower than 0.1 Hz can serve as an indicator of the ionospheric turbulence level. However, this part also contains low-frequency components of the interplanetary scintillations spectrum. For this reason, to determine the ionospheric scintillation index, we used the observational data of extended radio galaxies, the angular size of which is greater than a critical value for the interplanetary scintillations.

Fig.1 represents the data obtained in the session on October 24–31, 2011. The black dots show the change in the day average of the ionospheric scintillation index (SI) of two extended radio galaxies 3C55 and 3C47. The red dots show the power of interplanetary scintillations (PIS) - the energy of the high-frequency part of the scintillation spectrum of the compact source in the Crab Nebula.

It should be noted that on October 24, 2011, the Advanced Composition Explorer (ACE) satellite detected a sharp jump in the density and temperature of the near-Earth plasma, as well as a change in the solar wind speed from 350 to 500 km/s. The position of this event is marked with a green arrow in Fig.1. This event was also accompanied by a change in Dst geomagnetic index with the delay of 1.5 days, (low panel of Fig. 1) Interestingly, that according to the observation by Geostationary Operational Environmental Satellite (GOES), more than a day before the changes in plasma parameters at 10:25 UT 22.10.2011 there was a significant increase in X-ray emission and proton flux from the Sun, which indicates a powerful sporadic solar activity. In the Solar and Heliospheric Observatory (SOHO) coronagraph images, this time corresponds to a coronal ejection with a mass of $1.2 \cdot 10^{16}$ g and an energy of $6.2 \cdot 10^{30}$ erg of a halo type, i.e. directed towards the Earth, shown in Fig.2.

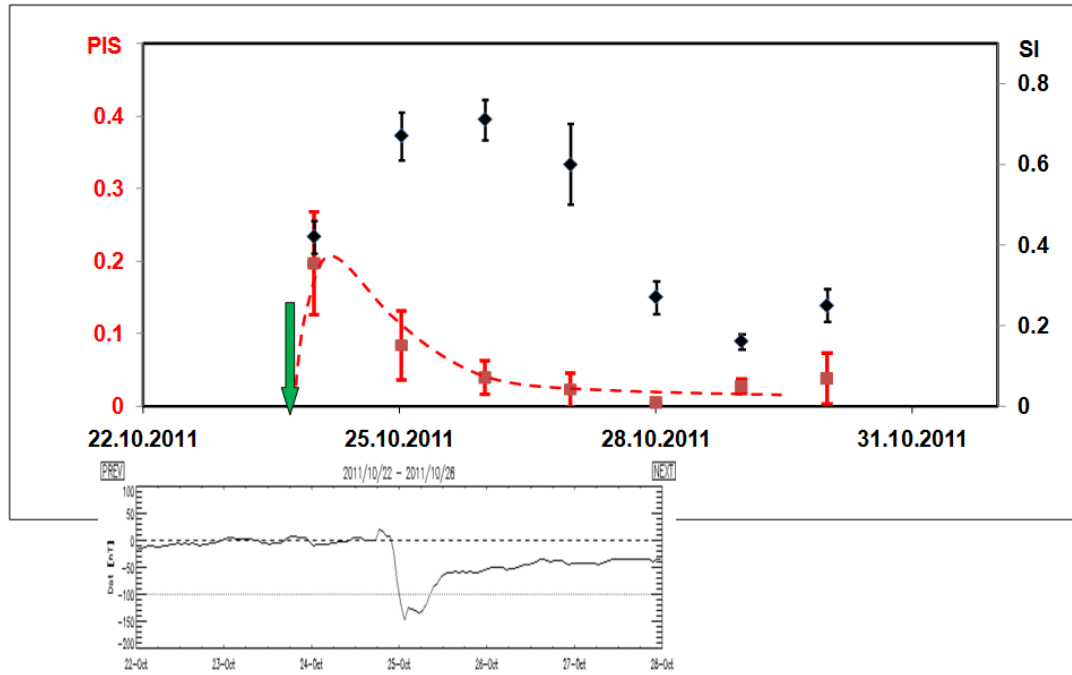


Fig.1. Ionospheric scintillation index (SI, black points), power of interplanetary scintillation (PI, red points) and Dst geomagnetic index from World Data Center for Geomagnetism, Kyoto

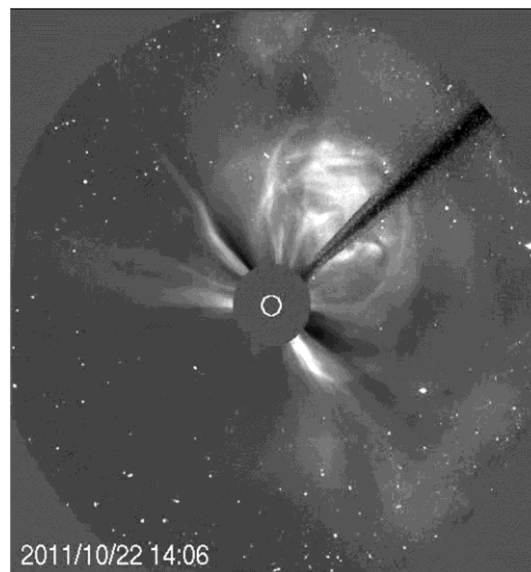


Fig.2. Coronal mass ejection recorded by SOHO C3 coronagraph 10/22/2011

Thus, a chain of successive events can be traced: a solar flare, a coronal mass ejection, a near-Earth shock wave, which caused an increase in interplanetary plasma turbulence, a magnetic storm, and an increase in the ionospheric scintillation index (ionospheric turbulence). This chain of events gives a hope for the possibility of a short-term forecast of a sharp deterioration in conditions of radio astronomy observations at the decameter wavelengths. However, in other cases of an increase in the ionospheric scintillation index, no previous powerful events on the Sun were found. So in the session on February 15–21, 2010, the increase in the ionospheric scintillation index was noted, which was accompanied by the increase in the turbulence of the

interplanetary medium (Fig. 3). Here, the interplanetary scintillation were also determined from observations of the compact source in the Crab Nebula, and the day-averaged ionospheric scintillation indices were obtained from observational data of the extended radio galaxies 3C288, 3C350, and 3C351.

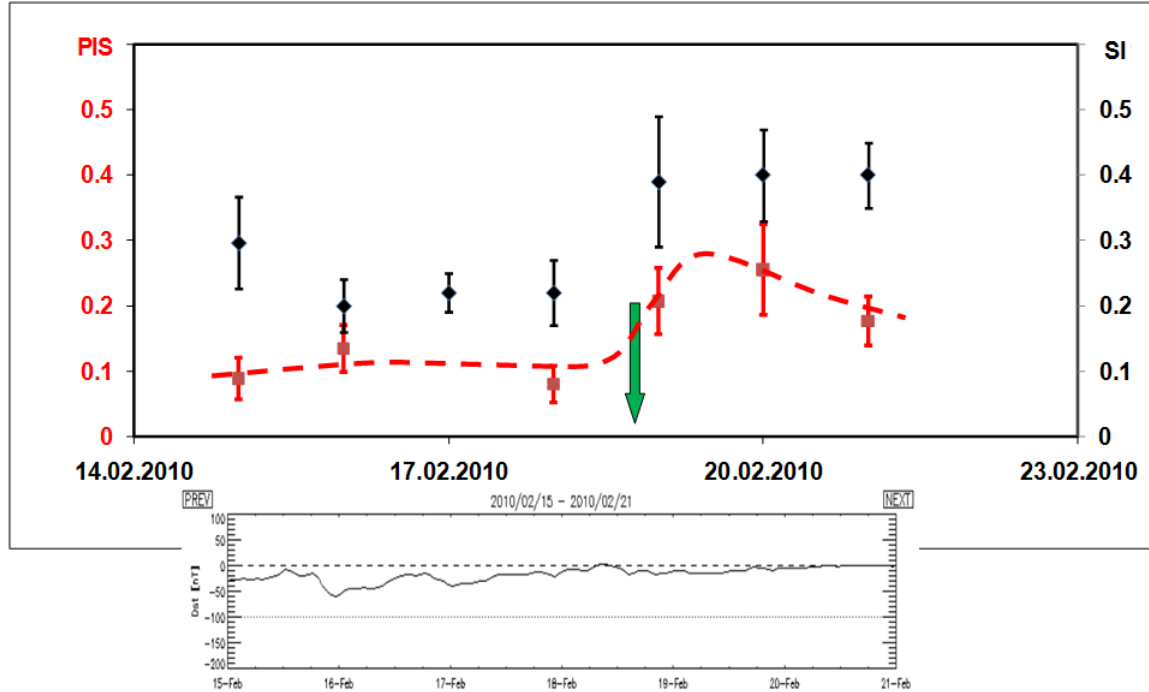


Fig.3. Ionosphere scintillation index (SI, black points), power of interplanetary scintillation (PI, red points) and Dst geomagnetic index from World Data Center for Geomagnetism, Kyoto

The presence of disturbances in the near-Earth solar wind is confirmed by the ACE data. However, in this case, the changes in the parameters of the near-Earth plasma were much less strong and fast, the solar wind speed, for example, changed from 400 to 450 km/s. Time of these disturbances is shown by arrow in Fig.3. There was no change in the geomagnetic index (low panel Fig. 3) and in the previous few days, there was no increase in the proton flux, and only small fluctuations in the intensity of the X-ray radiation were noted. Also, no significant coronal mass ejection was detected. It is possible that such complex of disturbances in the near-Earth plasma and solar activity can be associated with coronal holes and high-speed solar wind streams.

Conclusions

1. The processing of the archived data of radio sources observations with the UTR-2 radio telescope and the URAN interferometers was carried out. The data reduction made it possible to determine the magnitude of ionospheric and interplanetary scintillation separately.
2. A connection has been found between disturbances in the near-Earth interplanetary medium and the turbulence of the ionosphere.
3. The data obtained on the causes of the deterioration of the "radio astronomical weather" can be used for forecasting disturbances and planning the observations at the decameter wavelengths.

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