Low Frequency Adaptive Radio Astronomy: Application for Radio Interferometers

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Abstract

Using low frequency radio astronomical signals (RAS) to investigate pulsars and the Sun it is necessary to take into account possible distortions of RAS in the Earth ionosphere. However in contrast to modern navigation systems (GPS, GLONASS, GALILEO), in present-day radio astronomy a retrieve of ionosphere parameters has not been appropriately worked out yet. It collides with increasing requirements to accuracy of the analysis of a RAS amplitude profile and to the angular and polarizing resolution of radio telescopes of new generation. We have developed a method and software for calculation of the ionosphere rotation measure (*RM*) and the dispersion measure (*DM*). We used the ionosphere model IRI-2001, magnetic field model IGRF-10 and values of ionosphere total electron content as deduced from GPS measurements. The obtained values of the *DM* and *RM* were recalculated into characteristics of phase delay, Faraday amplitude modulation and polarization changes. We made estimations of radio interferometer angular error caused by ionosphere signal distortion.

1. Introduction

The investigation of pulsars radio emission is of great value for fundamental science. Operating at lower frequencies allows radiation from extremely distant radio pulsars to be detected. There is a great number of low frequency radio telescopes (RT): FIAN LSA (111 MHz; http://www.prao.psn.ru/radiotelescopes/telescopes.html), NANÇAY (from 150 MHz; http://www.obs-nancay.fr/a_index.htm), UTR-2 (25 MHz; http://www.ira.kharkov.ua/UTR2/) etc. Besides the huge low-frequency radio-astronomical array LOFAR (10-240 MHz; http://www.astron.nl/p/lofarframe.htm), consisting of 25000 receiving dipoles located on the area with diameter of about 350 km, is being constructed in the Netherlands. A similar array with 8000 dipoles MIRA (80-300 MHz; [1]) is being built in West Australia.

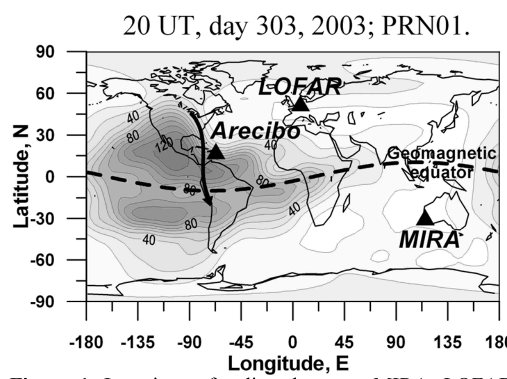

Figure 1. Locations of radio telescopes MIRA, LOFAR and Arecibo (black triangles). Trajectories of subionospheric points for satellites PRN01 at h=2000 km on October 30, 2003 are shown by curved lines.

The intensity of ionosphere effects is inversely proportional to the square of frequency [2], therefore the ionosphere distortions of RAS are presumed to be negligibly small in the frequency range more than 100 MHz, and it is not worthwhile considering them for the interpretation of observations. But this is quite wrong. Effects of the multiple-beam and polarization interference, which lead to strong distortion of intensity of RAS propagated in non-uniform medium (solar corona, ionosphere) were described in [3], where the ionosphere transfer characteristic (ITC) for RAS was introduced. However 25 years ago it was impossible to reconstruct this function for specific conditions yet. Nowadays tools of continuous and global monitoring of the ionosphere total electron content (TEC) based on GPS data and two-frequency satellite altimeters (TOPEX, Jason-1) have appeared). Modern ionosphere models such as IRI and NeQuick allow to calculate the main ionosphere parameters as well.

2. Calculation of the ionosphere transfer characteristic

The ionosphere phase delay $\Delta\phi$ is determined by the value of the TEC along line of sight (LOS) to a source [2]

$$\Delta\phi = \frac{8.44 \cdot 10^{-7}}{f} \int_S N_e ds \qquad (1)$$

where N_e - electron density, m^{-3}; f - frequency of the signal, Hz. The TEC value $\int N_e\, ds \equiv I$ defines a dispersion measure DM of a radio signal to calculate phase delay at different frequencies f.

If the signal polarization is linear or elliptical there is a significant amplitude effect that is caused by the rotation of the polarization plane (Faraday effect; [2]). In [4] such kind of modulation is defined as Faraday Amplitude Modulation (FAM). For a condition of "quasi-longitudinal propagating" the angle of the polarization plane rotation is defined by the expression [2]

$$\Omega = 2.365 \cdot \frac{10^4}{f^2} \int_S N_e B_0 \cos\theta ds; \qquad RM = 2.365 \cdot 10^4 \int_S N_e B_0 \cos\theta ds, \tag{2}$$

$$\Omega \approx 2.365 \cdot \frac{10^4}{f^2} \langle B_0 \cos\theta \rangle \cdot DM; \qquad RM \approx 2.365 \cdot 10^4 \langle B_0 \cos\theta \rangle \int_S N_e ds\,, \tag{3}$$

where B_0 - magnetic intensity, T; $<B_0 \cdot cos\theta>$ - average value of the product $B_0 \cdot cos\theta$ along the LOS (it can be calculated using a suitable magnetic field model); θ - angle between magnetic-field vector and LOS. The value $\int N_e B_0\, cos\theta\, ds$ has the character of a rotation measure. When the formulas (3) are used it is supposed that the magnetic field has small variations along the LOS, at least in the region where the electron density is not negligibly small.

The amplitude distortion of a linearly (elliptically) polarized signal received by a linear-polarization antenna is defined by the modulation function $M(t)$ [3]

$$A(t) = M(t) \cdot R(t); \quad M(t) = \sqrt{1 + a^2 + 2a \cdot \cos[2\Omega(t) + \varphi_0]}\,, \tag{4}$$

where $R(t)$ - input signal (entering the ionosphere); $A(t)$ - "output" signal; a - depth of modulation (the ratio of amplitudes of the electromagnetic wave components with right and left rotation); φ_0 - initial phase.

The set of formulas (1-4) allows us to calculate the effects of the ionospheric phase modulation, polarization plane rotation and Faraday amplitude modulation using known values of DM and RM. For the calculations it is necessary to have data of electron density or TEC values and magnetic field vector (which can be calculated using modern magnetic field model IGRF-10; http://www.geomag.bgs.ac.uk/gifs/igrf_form.shtml) along LOS. **Our main idea is to use a signal of navigation satellites (GPS, GLONASS, GALILEO) as a testing signal from a "reference" source located at minimal angular distance from a source studied.** Our project allows development of methods and systems of ADAPTIVE RADIO ASTRONOMY, adaptive to the non-uniform and non-stationary ionosphere, by analogy with known systems of adaptive optics intended to adapt optical telescopes to varying conditions of the optically non-uniform and non-stationary troposphere. Since in the near future the combined receivers GPS-GLONASS-GALILEO that can simultaneously observe about 30 satellites will appear, one can chose an appropriate satellite located on the minimal angular distance from the radio source under investigation. Nevertheless, it is necessary to use up-to-date ionospheric models to refine calculations. We made calculation using IRI-2001 in order to compare it with GPS data.

The results of our calculations were obtained for a frequency of 100 MHz. For different frequencies the form of dependences remains unchanged, but scale multipliers vary ($1/f$ for the phase, $1/f^2$ for the polarization angle). In order to calculate the modulation function $M(t)$ (4) it is necessary to set the depth of modulation a and the initial phase φ_0. In the context of a qualitative estimation of the ionosphere influence on radio astronomical signals, we chose the value $a=0.5$, which is characteristic of the elliptic polarization, and zero value for the initial phase φ_0.

3. The results of ITC calculation

In order to estimate limits of signal distortion, caused by ionosphere modulation, we chose a GPS satellite as a model of radio source. For the analysis we chose data of GPS site *PUR3* located in the proximity of RT Arecibo (http://www.naic.edu/), Puerto Rico, on October, 30th, 2003 (day 303) during strong geomagnetic storm. The geometry of

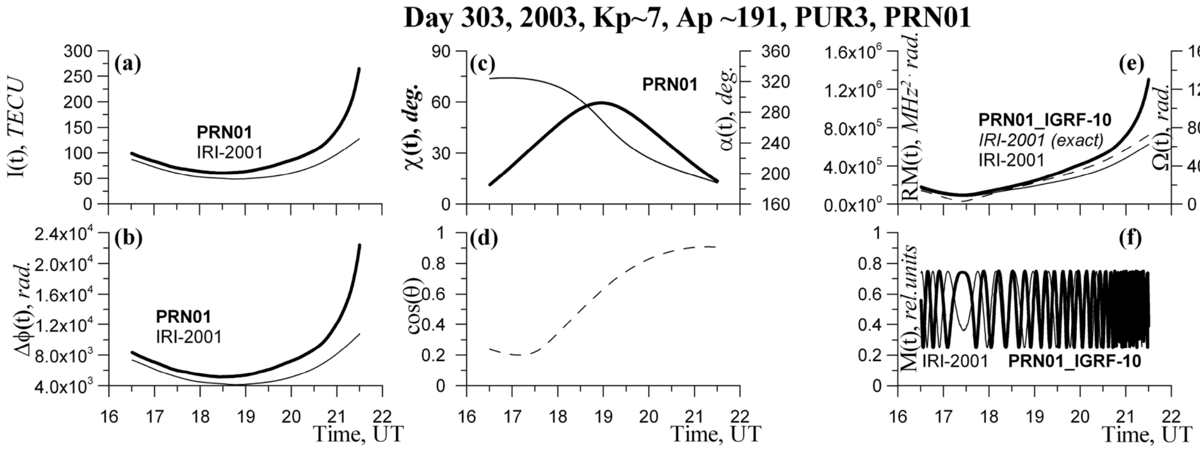

Figure 2. Ionosphere transfer characteristics in the Arecibo area (GPS site PUR3) for the strong geomagnetic storm on November 30, 2003. **a** – the slant TEC $I(t)$, deduced from PUR3 data (black curve) and from IRI-2001 modeling (gray curve). **c** – the LOS azimuth $\alpha(t)$ (gray line) and elevation $\chi(t)$ (black line). **d** – $\cos(\theta)$ dependence. **e** – *RM* deduced from experimental data (black thick line) and IRI modeling (gray thick line – "approximate" calculation; dashed line – "exact" calculation); the same curves - corresponding polarization angle $\Omega(t)$ for 100 MHz. For 100 MHz, the phase delay $\Delta\phi$, and modulation function $M(t)$ are shown in panels **b, f** (the indications coincide with those at panels **a** and **e** accordingly).

the experiment is presented in the Fig.1. Here spatial distribution of the vertical TEC, reconstructed from JPLG IONEX data for 20:00 UT (ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex/), is plotted. This time corresponds to the main phase of the magnetic storm, when the most significant redistribution of ionization was observed worldwide.

Values of slant TEC (Fig. 2a) exceeded 250 TECU (TECU=10^{16} m^{-2}). For PRN01 the angle between the LOS and magnetic field vector is decreased and $\cos[\theta(t)]$ approached 1.0 (Fig. 2d) providing the quasi-longitudinal propagation condition. The LOS azimuth to PRN-01 in the time interval 17-21 UT changed from northwest to southwest direction, where the so-called «hot spot» of increased ionization was formed (Fig.1). The ray penetrated into the area of the northern crest of the equatorial anomaly, where very high TEC gradients were up to 5-8 TECU for one degree on latitude. Experimental *RM* values (Fig. 2e) amounted to $1.4\cdot10^6$ $Mhz^2\cdot rad$ during daytime. For comparison the *RM* for radio pulsar PSR0943 +10 is $1.2\cdot10^6$ $Mhz^2\cdot rad$ [5]. The FAM *M(t)* period for 21-22 UT (Fig. 2h) is about 200-300 sec. The experimental values of the ionosphere phase delay (Fig.2b, black curve; see also Fig 3) vary from thousands radians at the maximal elevation χ to tens thousand radians at low elevation. It is obvious that phase delay will be significantly different for different RT (or different elements of a RT array). This can result in significant errors, when processing of very long base interferometer (VLBI) data. If d is VLBI baseline (m), the phase delay difference $\Delta\phi$ results in the error of radio source angular position $\delta\theta=c\Delta\phi/(2\pi fd)$.

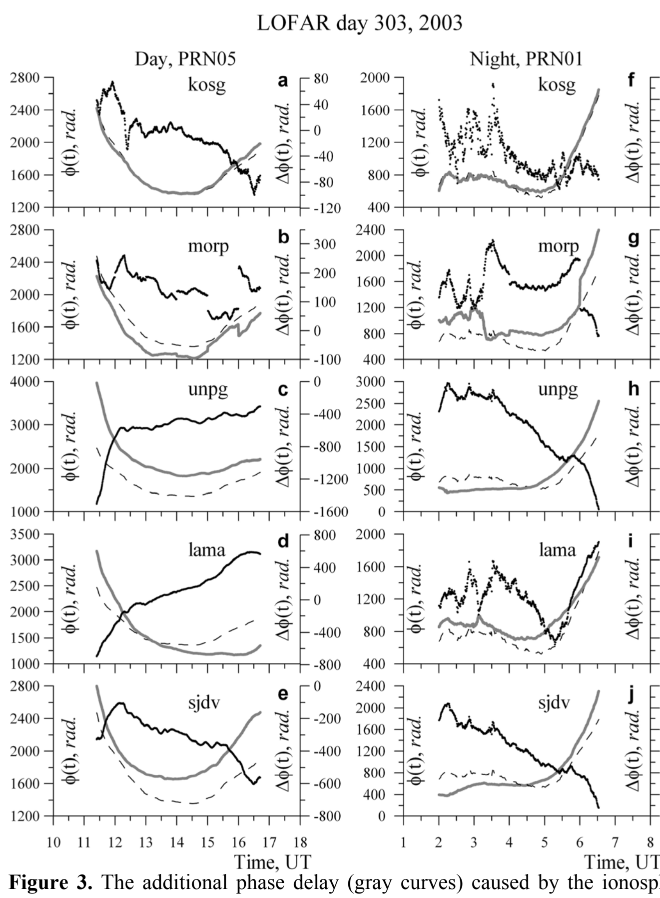

Figure 3. The additional phase delay (gray curves) caused by the ionosphere on October 30, 2003, and the phase delay difference (black curves) between the LOFAR "central point" (WSRT – dashed curve) and points of the VLBI system located in France (SJDV), Poland (LAMA), Great Britain (MORP), Italy (UNPG).

4. LOFAR VLBI mode

In addition to main complex in the complete LOFAR design, it is planned to create the antennas in France, Poland, Italy, and Great Britain for VLBI mode of LOFAR [6]. We chose GPS sites located there (see Fig. 4). For these sites we calculated the ionospheric phase delay ϕ along "receiver – GPS satellite" (for the day – Fig. 3*a-e* and night – Fig. 3*f-j*). Then, we calculated the phase delay difference for VLBI points against "central point" (we chose the site WSRT). A phase delay varied from 400 to 4000 radians for different elevations χ and azimuths α to the GPS satellite and locations of VLBI points. Even for rather close points KOSG and WSRT the $\Delta\phi$ values varied from +80 to -80 radians. For more distant VLBI point UNPG, the phase delay (Fig. 3c) difference amounted to 1500 radians or 50% in relation to the absolute phase delay value. For f=100 *MHz* and d=1200 *km* (an approximate distance between WSRT and UNPG sites), the 1500 radians results in the angular distance error of 2.05′. Meanwhile, the LOFAR angular resolution for f=120 *MHz* and d=100 *km* is 6.3″ [7].

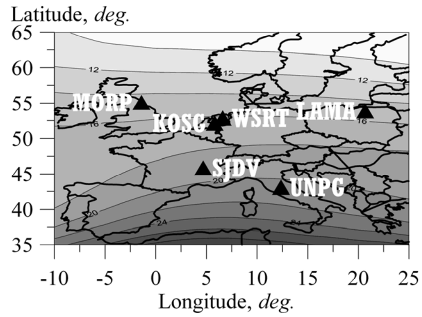

Figure 4. The experiment geometry for the LOFAR VLBI system. Triangles mark location of the GPS sites. In the figure, global ionosphere maps are plotted for October 30, 2003, 14:00 UT.

5. Conclusion

The rotation of the polarization plane and the FAM should be taken into account when analyzing the linear polarized radio pulsars emission. The modulation of impulse pulsar amplitude [5] can be caused by FAM in the ionosphere. Besides, the ionosphere influence gives rise to a more significant VLBI error in comparison with the VLBI potential resolution.

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