Polarization Sounding of Pulsar Magnetosphere

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Neutron Stars and Pulsars: Challenges and Opportunities after 80 years

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Abstract

A possibility in principle of a polarization sounding of pulsar magnetosphere using intrinsic pulsar emission as a probe signal is examined for modern radio telescopes of the meter and decameter wave ranges. Different models of the pulsar magnetosphere at altitudes higher than a radius of critical polarization are used. The propagation medium besides magnetosphere (interstellar medium, interplanetary medium, Earth ionosphere) is described by the stratified model in which each layer has its own density of free electrons, vector of magnetic induction as well as spatial and temporal fluctuation scales of these parameters.

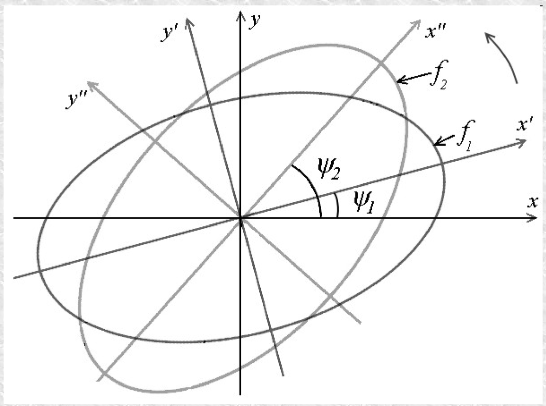
Mathematically the stratified model of the propagation medium is presented as an overdetermined system of linear equations. This system is linear in unknown parameters of polarization. Solving the inverse problem, it is possible to obtain the estimations of all polarization parameters for different frequencies and pulsar pulse longitudes (for example as the Stokes parameters). Namely the frequency dependence of the polarization parameters of the pulsar radio emission obtained in the broad band for a selected pulse phase will make possible sounding of the pulsar magnetosphere deep inside.

Proposed method of estimation of polarization parameters gives an opportunity to select the best model of pulsar magnetosphere via a comparison with the observational data.

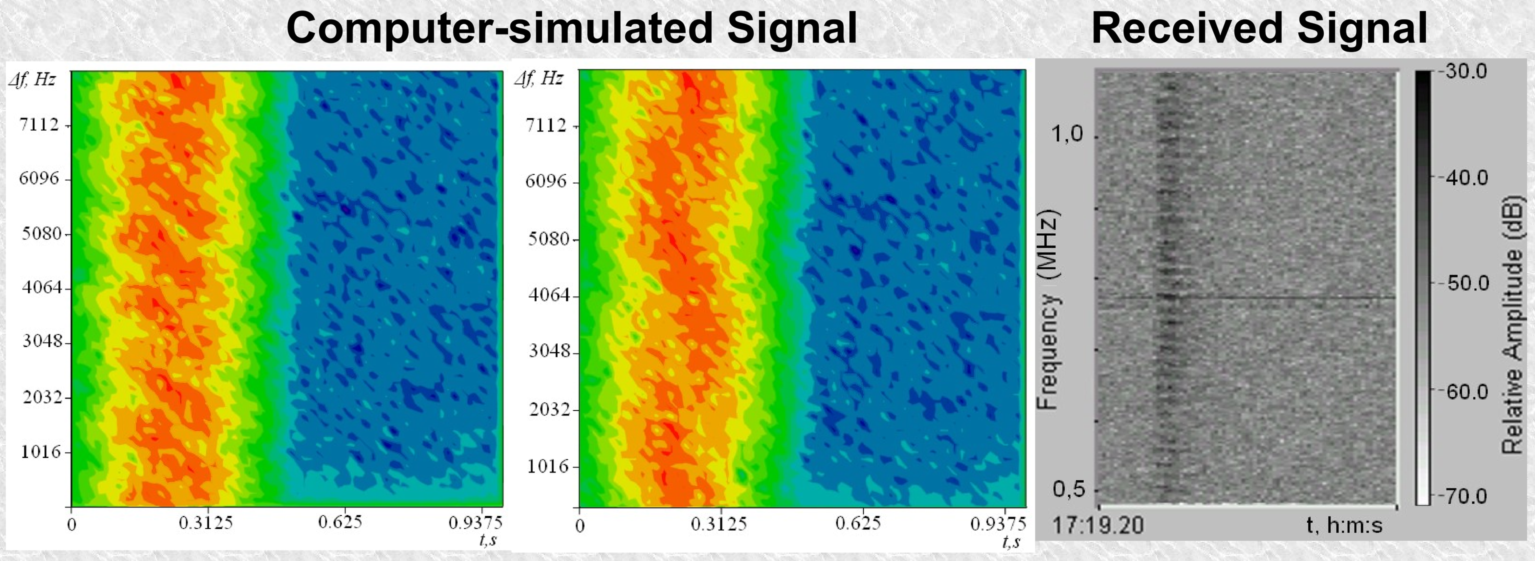
Faraday Rotation

$$n_o(\omega)=\sqrt{1-\left(\frac{\omega_p}{\omega(\omega-\omega_H)}\right)^2}\qquad \omega_H=\frac{e\langle\beta\rangle}{m_e c}$$

$$n_x(\omega)=\sqrt{1-\left(\frac{\omega_p}{\omega(\omega+\omega_H)}\right)^2}\qquad \omega_p=\sqrt{\frac{4\pi e^2\langle N_e\rangle}{m_e}}$$



Instanteneous Spectra of

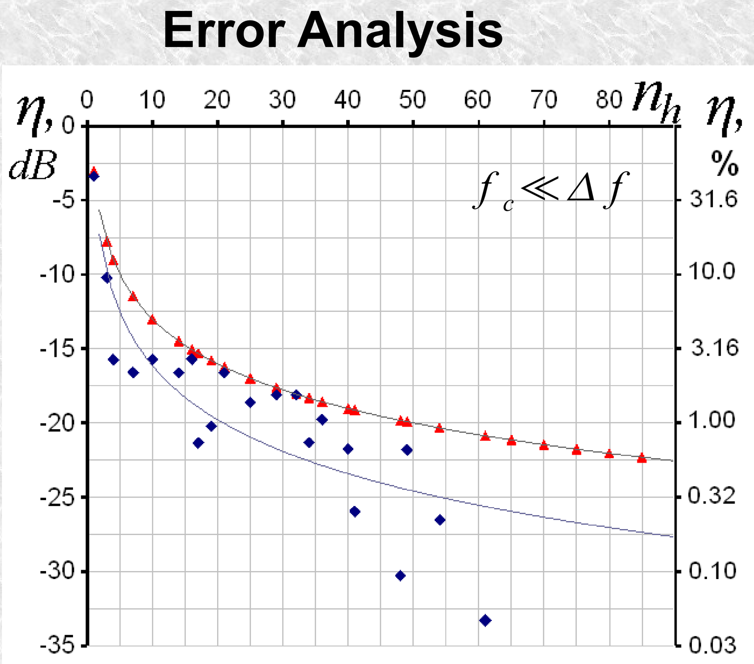


F = 20 MHz **F = 30 MHz**
Model Value of *RM*

Single Pulse PSR B0809+74, F = 23.7 MHz, RM = 11.7 rad/m²

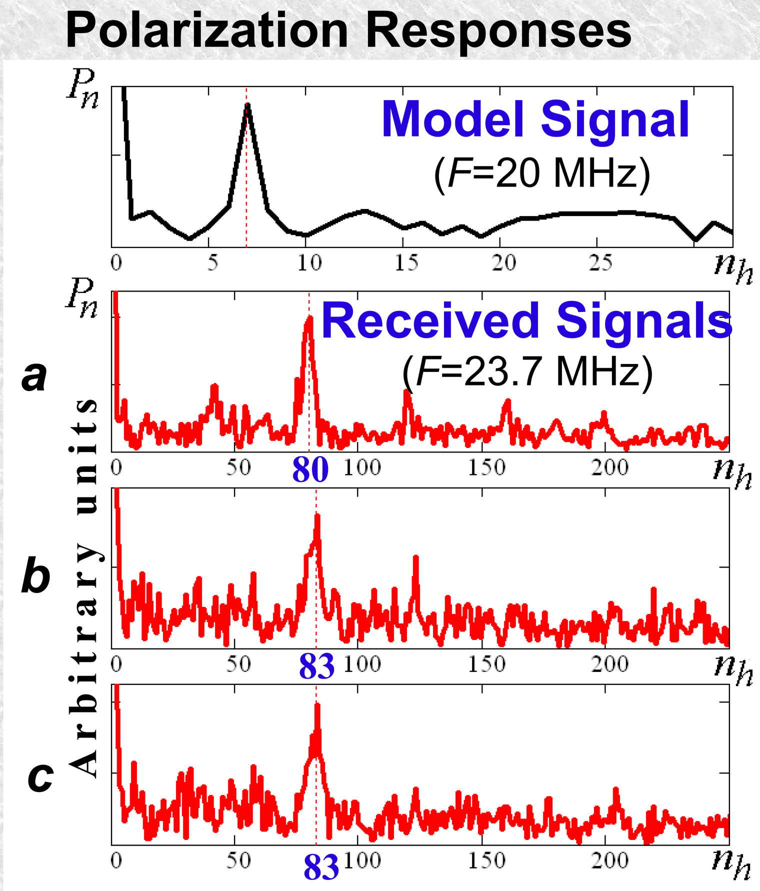
$$\Delta\psi(RM,f)=c^2RM\left[\left(\frac{1}{f_c}\right)^2-\left(\frac{1}{f_c+\Delta f}\right)^2\right]\qquad \Delta\psi=\pi\qquad RM=\frac{\pi}{c^2}\left[\frac{f_c^2(f_c+\Delta f)^2}{(f_c+\Delta f)^2-f_c^2}\right]$$

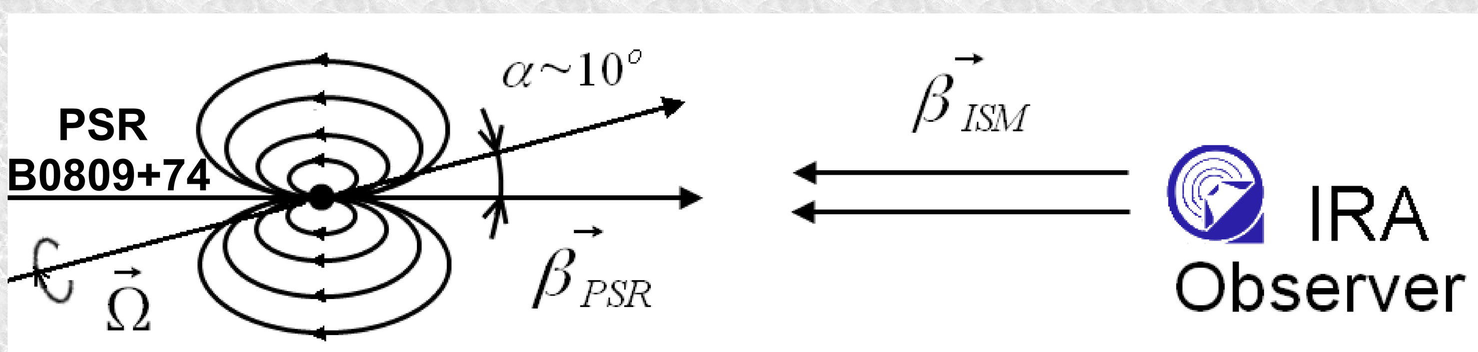
Error Analysis



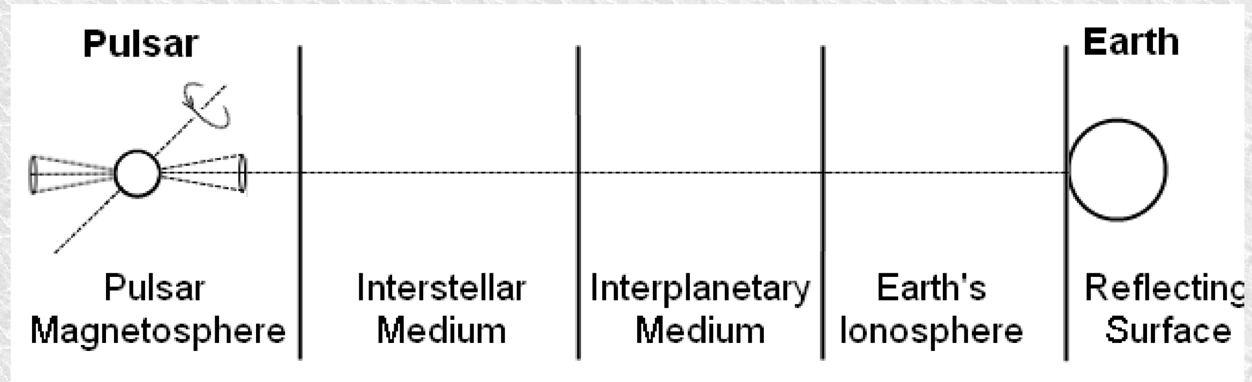
Model Signal: Error = 2.15 % (max=7.1%)
Received Signals: Max error = 0.6%,
Obtained deviations : ΔRM_{max} = - 0.94 rad/m²
a) 4.1% → *RM*=-12.18 ± 0.073 rad/m²
b,c) 8,0 % → *RM*=-12.64± 0.075 rad/m²

Polarization Responses





Stratified Model of the Propagation Medium

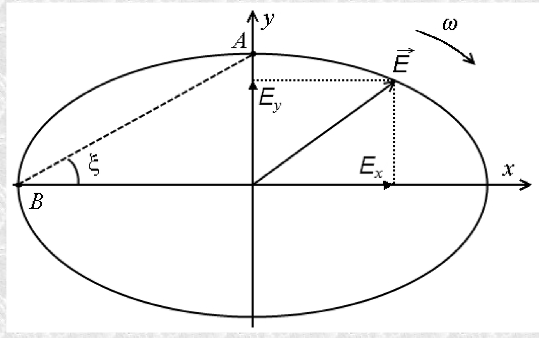


$$\vec E^{rec}=\prod_i^N DM_i RM_i \vec E^S$$

$$\vec E^S=\left(\prod_i^N DM_i RM_i\right)^{-1}\cdot\vec E^{rec}$$

Simulation of the Pulsar Signal with the Elliptical Polarization

$$\vec{\dot E}^s(\omega,x,y,z)\to\begin{bmatrix}\dot E_x(\omega)\\ \dot E_y(\omega)\\ 0\end{bmatrix}\qquad \begin{cases}\dot E_x(\omega,z)=A\cdot e^{-i\omega t}\\ \dot E_y(\omega,z)=B\cdot e^{-i\omega t-\frac{\pi}{2}}\\ \dot E_z(\omega,z)=0\end{cases}$$

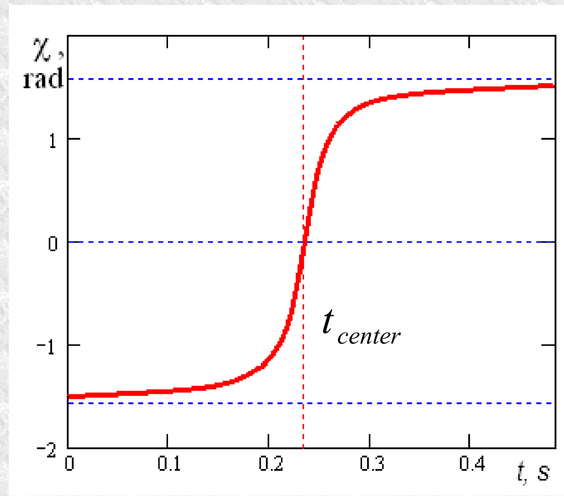


Transition Between Different Frame of Reference

$$\begin{bmatrix}\dot E_x\\ \dot E_y\end{bmatrix}=\frac{1}{\sqrt2}\begin{bmatrix}1&1\\ i&-i\end{bmatrix}\begin{bmatrix}\dot E_r\\ \dot E_l\end{bmatrix}\qquad \begin{bmatrix}\dot E_r\\ \dot E_l\end{bmatrix}=\frac{1}{\sqrt2}\begin{bmatrix}1&i\\ 1&-i\end{bmatrix}\begin{bmatrix}\dot E_x\\ \dot E_y\end{bmatrix}$$

Position Angle of the Model

$$\chi=arctg\left(\frac{t-t_{center}}{k}\right)$$



Eikonal Equation: $\nabla\varphi(\omega)=n(\omega)\vec k(\omega)$

$$\frac{d\varphi(\omega,z)}{dz}=n(\omega,z)k(\omega,z)=n(\omega,z)\frac{\omega}{c}$$

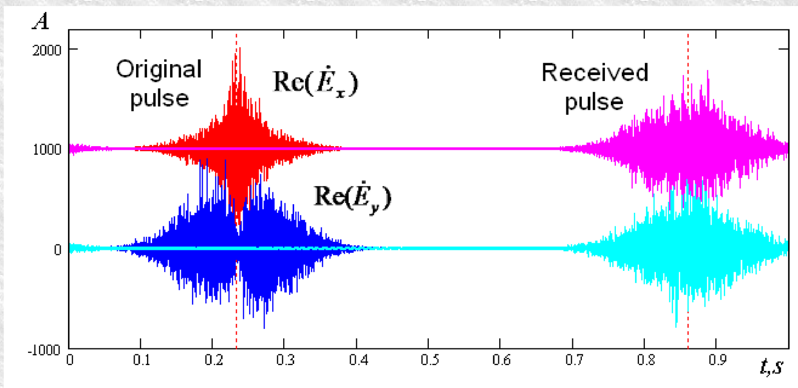
$$\varphi(\omega)\approx\omega\frac{L}{c}-\frac{1}{\omega}\frac{2\pi e^2}{m_e c}\int_0^L\langle N_e(z)\rangle dz-\frac{1}{\omega^2}\frac{2\pi e^3}{m^2c^2}\int_0^L\langle N_e(z)\rangle\langle\beta(z)\rangle dz$$

$$\alpha(\omega)\approx\frac{1}{\omega}\frac{2\pi e^2}{m_e c}\int_0^L\langle N_e(z)\rangle dz=\frac{4\pi^2e^2}{m_e c}DM\frac{1}{f}$$

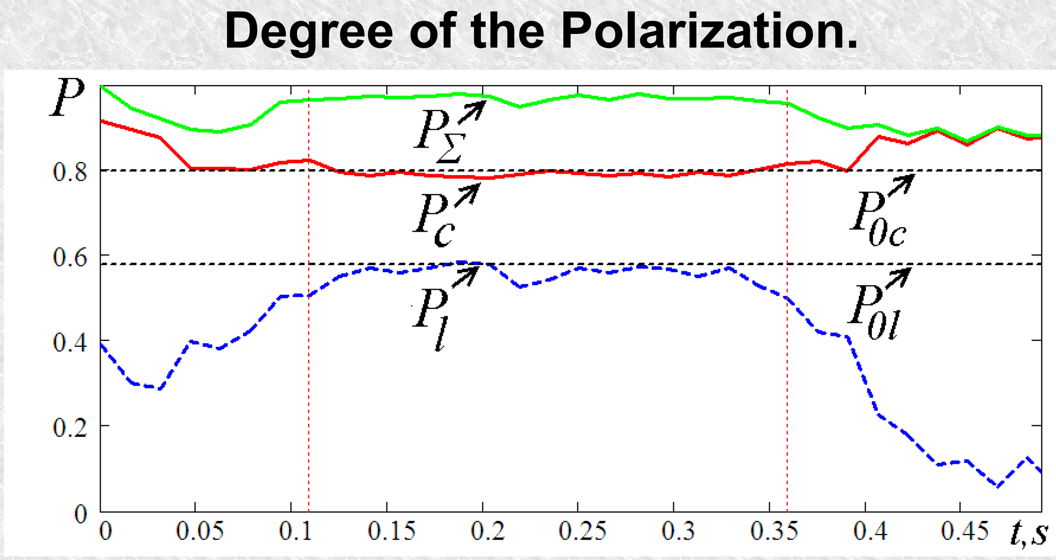
$$\psi(\omega)\approx\frac{1}{\omega^2}\frac{2\pi e^3}{m^2c^2}\int_0^L\langle N_e(z)\rangle\langle\beta(z)\rangle dz=RM\lambda^2$$

Can be represented as 3 term. The first term is the constant delay, second is responsible for dispersion delay, third shows the influence of magnetic field

Simulated Pulse



Degree of the Polarization.

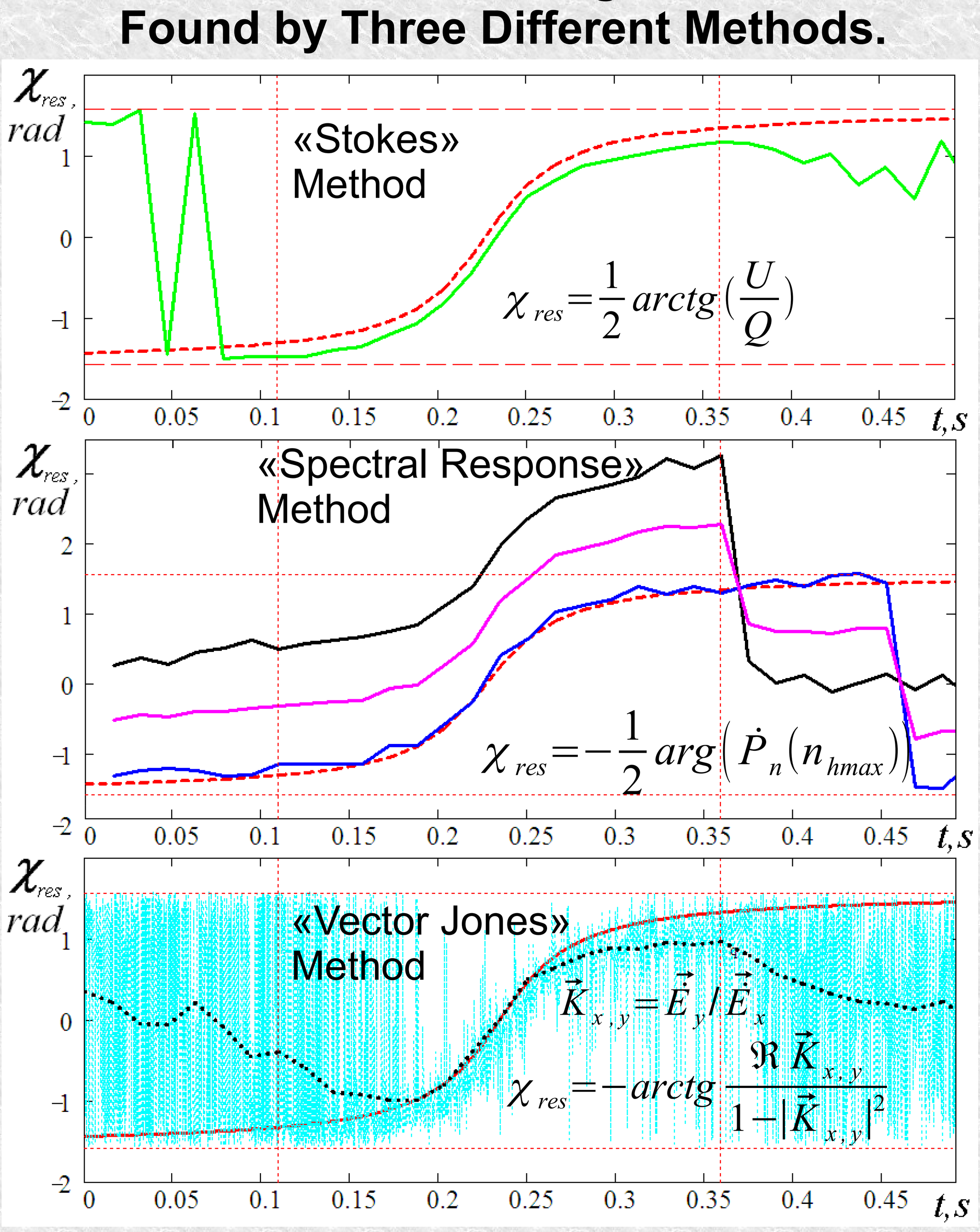


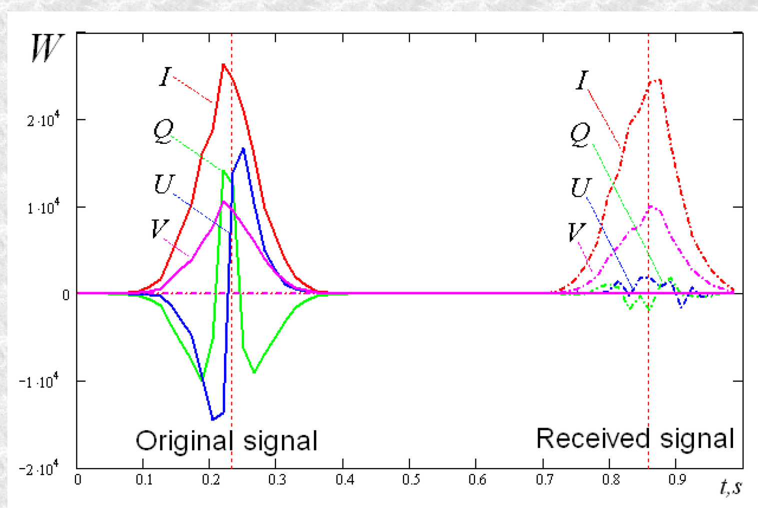
Stokes Parameters and its Representation in the Form of Polarization Tensor

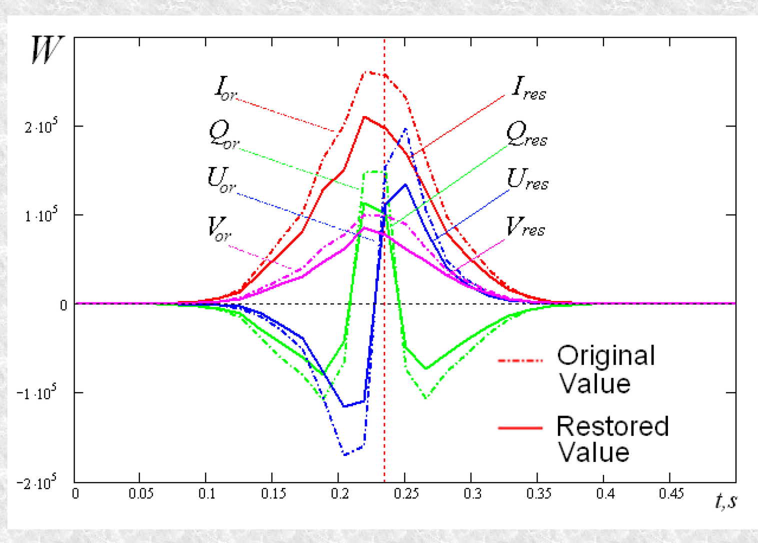
$$I=\begin{bmatrix}I_{xx}&I_{xy}\\ I_{yx}&I_{yy}\end{bmatrix}=\frac{c}{4\pi}\begin{pmatrix}\langle E_x(t)\cdot\overline{E_x(t)}\rangle&\langle E_x(t)\cdot\overline{E_y(t)}\rangle\\ \langle E_y(t)\cdot\overline{E_x(t)}\rangle&\langle E_y(t)\cdot\overline{E_y(t)}\rangle\end{pmatrix}$$

$$I=A^2+B^2+N^2\qquad I=I_{xx}+I_{yy}$$
$$Q=(A^2-B^2)\cos(2\chi)\qquad Q=I_{xx}-I_{yy}$$
$$U=(A^2-B^2)\sin(2\chi)\qquad U=I_{xy}-I_{yx}$$
$$V=(A^2+B^2)\sin(2\xi)\qquad V=i(I_{yx}-I_{xy})$$

Position Angle Found by Three Different Methods.







Conclusions:

The direct and inverse problems of determining the polarization parameters of elliptically polarized signal propagating through interstellar medium were solved by numerical methods. An eikonal equation used for modeling gave an opportunity to take into account the Faraday effect and cold plasma influence, i.e. presence of frequency dependent dispersive delay.

A method of estimating the rotation measure and position angle with an error below 2.5% is proposed. This method allows us to recover the Stokes parameters in a reference frame associated with a pulsar. The position angle was found by three independent methods.

For an antenna with two orthogonal polarizations, we have restored all Stokes parameters with admissible error that does not exceed 10% at 20 MHz.

It was found that ISM magnetic field and pulsar magnetic field have opposite directions.