V Meeting on Astrophysical Spectroscopy A&M DATA - Astronomy & Earth Observations AsSpectro2023: September 12-15, 2023, Palić, Serbia

VLF propagation parameters modeling related to low intensity solar X-ray flares

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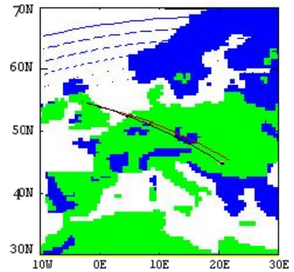
Simultaneous monitoring of Very Low Frequency (VLF) radio signals (3 - 30 kHz), transmitted within Earth-Ionosphere waveguide from USA (NAA/24.0 kHz), GB (GQD/22.1 kHz), Australia (NWC/19.8 kHz), Germany (DHO/23.4 kHz), Italy (ICV/20.27 kHz) and France (HWU/18.3 kHz) towards Serbia and registered by narrowband Absolute Phase and Amplitude Logger (AbsPAL) BEL receiving system, stationed at the Institute of Physics in Belgrade, was carried out.

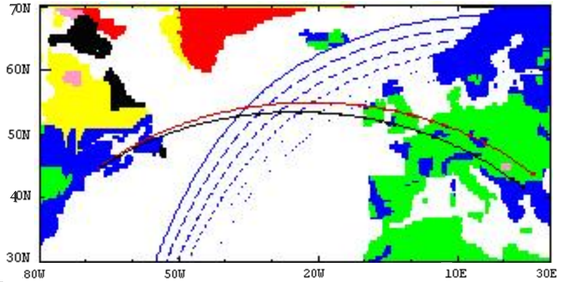
Low intensity Solar flare (SF) events during quiet solar conditions with low background X-ray radiation were surveyed and analyzed.

Numerical modeling of VLF propagation parameters of selected events on observed signals and obtaining related perturbed D-region (50 - 90 km) ionospheric conditions was conducted by means of Long Wave Propagation Capability (LWPC) program routine. Based on the Wait's model of the lower Ionosphere, electron density height profiles were estimated.

Possible Great Circle Paths (GCPs) for some of the simultaneously monitored VLF signals emitted towards Belgrade



GQD signal propagates along WNW-ESE mostly overland path long ≈2 Mm



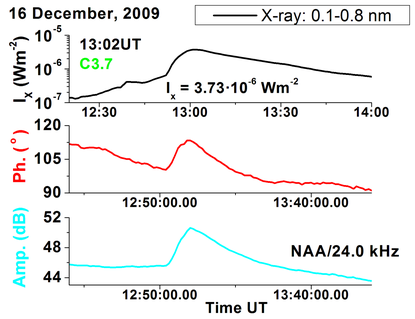
NAA signal propagates along W-E mostly oversea path long ≈6.5 Mm

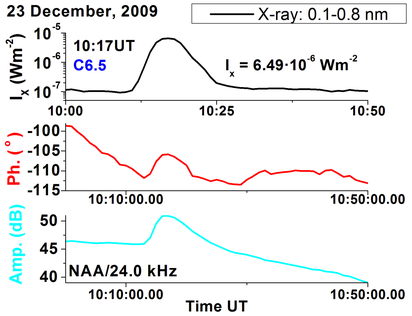
VLF signal (kHz)	Transmitter location	Power (kW)	GCP_BEL* (km)
NAA/24.0	Maine, USA (44.63° N; 67.28 °W)	1000	6547
GQD/22.1	Skelton, UK (54.72° N; 2.88° W)	500	1982

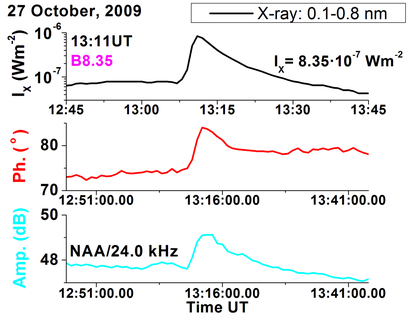
*BEL receiver (44.85° N; 20.38° W)

VLF propagation parameters modeling related to low intensity X-ray SFs

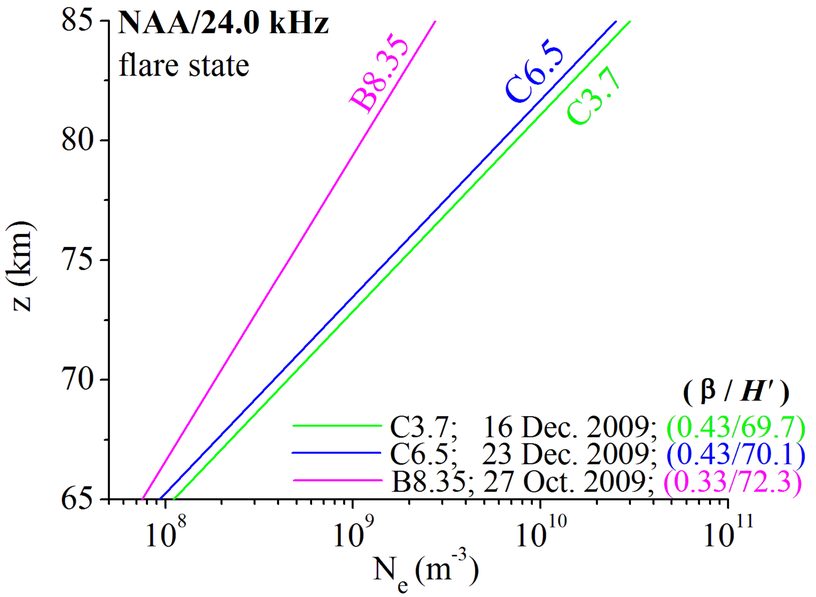
Case of NAA/24 kHz signal







X-ray irradiance (black) diurnal variation and NAA signal amplitude (red) and phase (blue) variations related to three low intensity SFs from 2009: C3.7, C6.5 and B8.35



Electron density height profiles $N_e(z)$ (m^{-3}) in 65 - 85 km altitude range for case of NAA signal, related to X-ray irradiance peak of three low intensity SFs from 2009: C3.7 in green, C6.5 in blue and B8.35 in pink

Possible GCPs for monitored VLF signals were calculated by LWPCv21 (Ferguson, 1998) code based on Long Wave Propagation Model developed from Wait's theory (Wait, 1962).

Electro-conductivity maps incorporated within prvwPlot subroutine are based on real electro-conductivity data globally measured. Areas of land with low electro-conductivity ($\sigma_g \approx 3 \cdot 10^{-3}$ S, $\varepsilon_r = 15$) are given in yellow, red and black. Areas of somewhat higher electro-conductivity such as most of the land ($\sigma_g = 3 \cdot 10^{-2}$ - $1 \cdot 10^{-1}$ S, $\varepsilon_r = 15$) are given in blue and green. Areas of high electro-conductivity such as water regions ($\sigma_g = 4$ S, $\varepsilon_r = 81$) are given in white.

In model of Earth-ionosphere waveguide for VLF waves propagation, electron density height profile in the lower ionosphere is characterized (Wait and Spies, 1964) by a pair of two parameters: sharpness β (km^{-1}) and reflection height H' (km).

Electron density height profile $Ne(z)$ (m^{-3}) in lower ionosphere, for given parameters sharpness β (km^{-1}) and reflection height H' (km), was calculated using expression designed for sunlit daytime ionospheric conditions (Wait and Spies, 1964):

$$Ne(z, H', \beta) = 1.43 \cdot 10^{13} e^{-0.15 H'} e^{(\beta - 0.15)(z - H')}$$

By means of LWPCv21 code (Ferguson, 1998), propagation paths of VLF signals were simulated and the goal was to estimate the best fitting pairs of parameters (β/H') to yield values closest to real measured phase delay and amplitude at Belgrade receiver site, for characteristic states on analyzed VLF signals. Vertical electron density height profiles through ionospheric D-region (50 - 90 km) were calculated using above given relation.

Acknowledgements

This work was funded by Institute of Physics Belgrade, University of Belgrade, through grant by the Ministry of Science, Technological Development and Innovations of Republic of Serbia. Authors thank D. Šulić for instrumental set-up.

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