PROCEEDINGS OF SCIENCE

Gamma-ray bursts detection capabilities of a sudden ionospheric disturbance detector

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Cosmic gamma ray bursts(GRB) are high energetic photos resulting from astrophysical events within and beyond our galaxy. Their energy is deposited in the upper atmosphere by ionization of the constituent atoms and molecules. The resulting plasma affects the absorption and hence the propagation of radio waves in the VLF range which can be used to detect and analyse GRB. In this work we are investigating the response of a SID monitor to GRB by modelling the ionization by GBRs in the ionosphere and the effects on the radio wave propagation. Subsequently we discuss the potency of the SID monitor for detection and analysis of GRBs and the implications to space-weather monitoring and applications.

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1. Motivation

Experimental observations of high-energy phenomena require large scale detectors or detector assemblies (arrays) in order to integrate the entire primary event energy deposited in the detection medium. Practically for astrophysical and cosmic rays observations, different regions of the Earth are utilized as detector volumes e.g. the oceans (Pacifflc Ocean Neutrino Experiment, P-ONE), the polar ice caps (IceCude neutrino detector[1]) the atmosphere e.g. Cherenkov Telescope Array Observatory (CTAO), The Cosmic-Ray Energetics and Mass investigation (CREAM), etc.). Additionally the complexity of the detectors and the required data treatment very sophisticated. The instruments are often expensive and require considerable investments.

The motivation of this work comes from potential for astrophysical events observations using the Earth's atmosphere. Ionisation effects by high energy photon radiation from astrophysical events in the Earth's atmosphere and significant interactions occur at altitudes of about 70 km where the air density and composition favours X-ray from solar flares and gamma-rays energy deposition. The higher density does not allow long lasting high electron concentration and the equilibrium under the current radiative input is quickly re-established with the flux reduction.

The idea that sources from outer space can produce measurable effects in the lower atmosphere was investigated by VLF methods [3, 5, 6] and observed already by [4]. The principle is based on refraction of radio-waves by the lower atmosphere. Very Low Frequency (VLF) radio signal is used to probe the state of the ionospheric D-layer (typical altitudes about 70 km). The degree of ionisation is evaluated by the amplitude of the refracted signal. This amplitude depends on the fraction of refracted and absorbed or attenuated signal. The latter depend on the electron content in the interaction (refraction region). Quantification of the amplitude of these peaks can be used to check theories and obtain information about the physics of the VLF ionospheric propagation. Also, it can be used for space-weather applications and what is the subject of this work - gamma-ray bursts (GRB) analysis.

2. Instrument, data and modelling tools

The instrument used in this work is a Sudden Ionospheric Disturbance (SID) monitor by Stanford Solar Center model SuperSID [8]. The detector is installed at the Geophysical Center of the Royal Meteorological institute of Belgium in Dourbes, coordinates 4.5971938, 50.0984719. The receiver antenna is constructed as a decagon with a circumradius of 1.5 meters and about **35** windings.

The detector logs data every 5 seconds from 13 VLF emitters. The most consistent results are observed for three nearest to the receiver transmitters: Rosnay, France, 20.9 kHz, and the two emitters at Anthorn, UK emitting at 19.6 and 22.0 kHz. Due to sender stability and signal quality, in this work we will use the 19.6 kHz wave signal from Anthorn, UK, emitting at about 550 kW power.

The night time signal is mainly from reflections in the upper ionospheric layers as the signal travels through the poor in electron content lower D and E layers. The amplitude can be constant or exhibit regions (intervals) with lower values due to absorptions in sporadic regions (sporadic E-layers) or resulting from interferences. The maximum value from the night time region (the after sunset of the previous day and sunrise of the current day) is used as a maximum amplitude of the received signal (Fig.1).

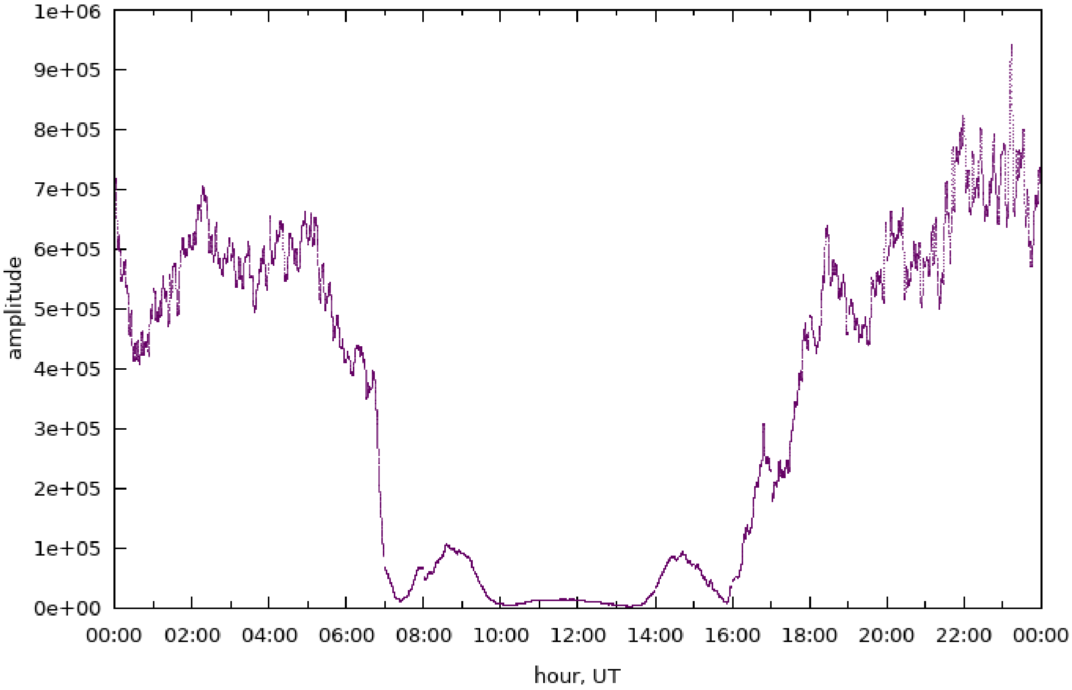

Figure 1: Daily variations of the signal amplitude from Anthron, UK (19.6 kHz), date: 2022-11-26 showing very narrow usable detection window from 9:45 through 13:30.

With the establishment of the D-layer, the refracted signal amplitude follows regular pattern depending on the solar irradiance (i.e. solar azimuth angle) (Fig. 1). To evaluate the latter we make the assumption that the signal makes 1 hop on its way to the receiver, and the altitude of the D-layer is about 70 km. The point of refraction is at the midpoint between the receiver and the transmitter with coordinates of about 0.123790, 53.037657.

The maximum amplitude for each day is taken from the plateau during the night time and then the refraction and absorbed part can be determined providing the emitter power is constant during the following hours. This value then is used to normalize the observations in order to compare different days.

The baseline signal during the daylight period is modelled from the solar azimuth at the give location and altitude of the refractive regions and subsequently corrected for the current solar activity using the $F_{10.7}$ index.

During the daylight period solar flares produce peaks of different amplitude. As a first step we will try to quantify this amplitude. Data observations shows that it does depend on the time of the day, the magnitude of the flare and the solar activity index $F_{10.7}$.

3. Baseline amplitude

The baseline amplitude during day time is the amplitude after the establishment of the D-layer which allows the detection of solar flares and GRBs. To quantify the amplitude of the flare observations, we need to model the secular observations. Given the limited data modelling of these variations is not possible at this point. The D-layer ionisation can be correlated to the hydrogen Ly-α line but measurements data of this parameter is not readily available. According to [7], $F_{10.7}$ can be used to model Ly-α which was used in our work. The resulting correlations however, 0.21 v $F_{10.7}$ vs. 0.16 with the composite Ly-α calculated from [7] are not satisfactory to obtain a quantifying result.

4. Solar flares observations vs. SID amplitude

The response of the D-layer to solar flares can be used to evaluate the response to GRB. The challenge here is to quantify the observations and determine the threshold for detection and also for observations analysis. In order to detect solar flares, the D-ionospheric layer have to be well established. Typically a solar flare is seen as a peak similar to the X-ray observation from the GOES satellites. In Fig. 2 the solar flares from 2022-03-23 are plotted where solar flares of class C were detected throughout the daylight variations of the signal. The similarity in the observations with the GOES X-ray detector results may allow us to quantify the amplitudes of the SID observed peaks vs. the flux density of the solar flares.

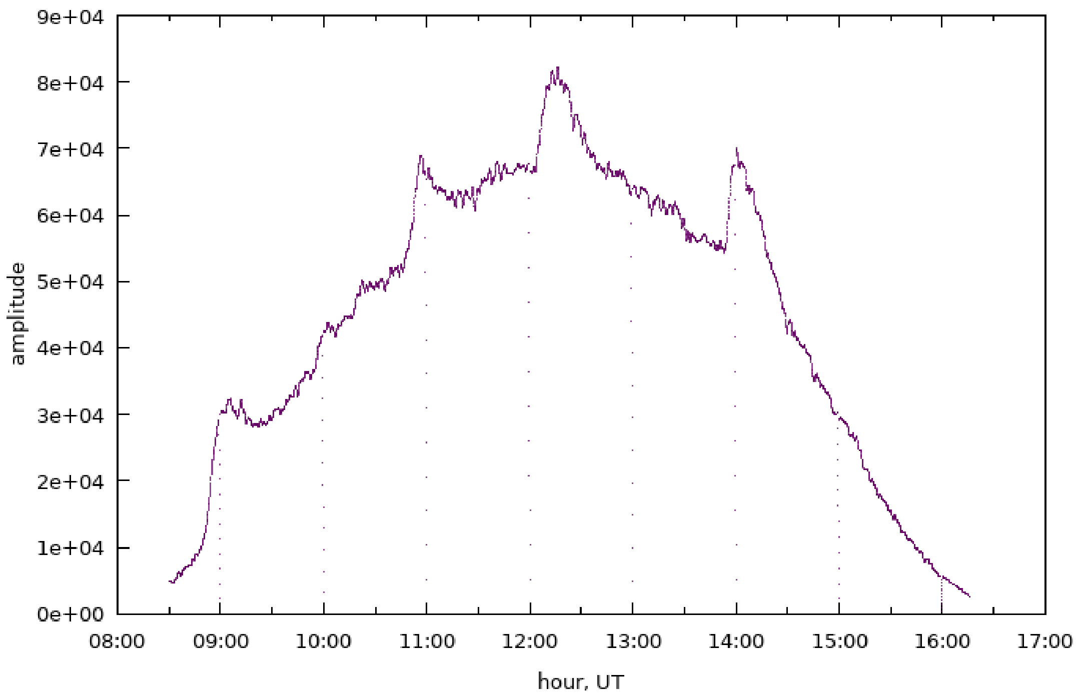

Figure 2: Solar flares as observed by the Sudden Ionospheric Detector (SID) monitor - 2022-03-23: the peaks correspond to class C solar flares.

Two months observations are plotted in Fig. 3. The values obtained by taking the absolute amplitude of the peak from the SID observation and removing the baseline (that is the signal amplitude without the peak due to the solar flare). Further, the values are corrected for the solar zenith angle at the time of the peak maximum. The effect of this correction on the flare peaks is very small.

The values of the observed amplitudes ψ vs. the flare flux ϕ are modelled by a two constants logarithmic function of the form $\psi = aln(\phi) + b$ plotted in Fig. 3.

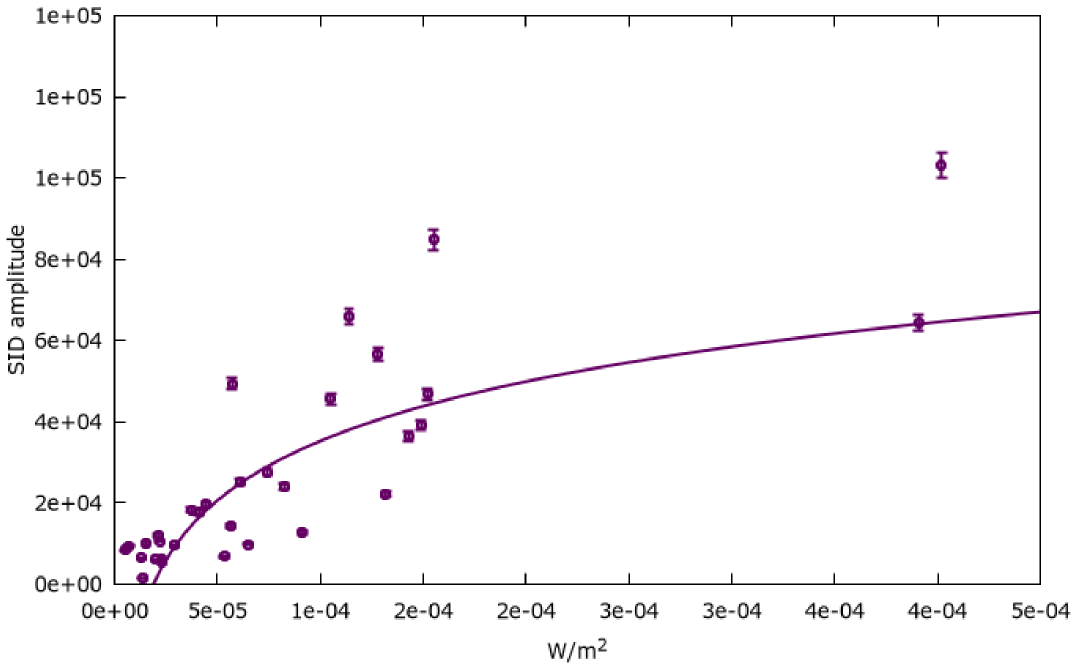

Figure 3: SID response amplitude as a function of the solar flare energy and flux.

5. Solar flare ionization and D-layer electron density

In the previous section an empirical relation between the observed amplitude and the energy of the solar flare was obtained. Another approach is to evaluate the ionisation due to solar flare and use it in order to obtain the amplitude of the refracted wave. Here we use the Monte-Carlo transport code GEANT4[2] to obtain the number of electrons within a target region of the ionospheric D-layer. The latter was approximated by a layer of thickness 10 km at an altitude of 70 km. Because the air density at this altitude is small, to simplify the simulations, we assume that the temperature and the pressure is constant within this region.

The energy flux for the simulations was taken from a C-class solar flare observed at noon UT on 2022-03-23 by GOES (Fig. 4). From this the photon flux was obtained for photon energies uniformly distributed between 3 and 25 keV. The attenuation effect of the upper atmosphere (from 70 to 200 km) was introduced with a thin volume with the same mass attenuation coefficient as the atmospheric part above the D-layer. The obtained electron densities produced per second in the case of the class C solar flare from Fig. 4 is about $21.6 \pm 7.5{\times}10^6$ electrons/m^3/s.

6. Discussion

The empirical relation between the observed SID amplitude and the flare flux obtained in section 4 can be already used for basic evaluation of the intensity of the impact photon radiation.

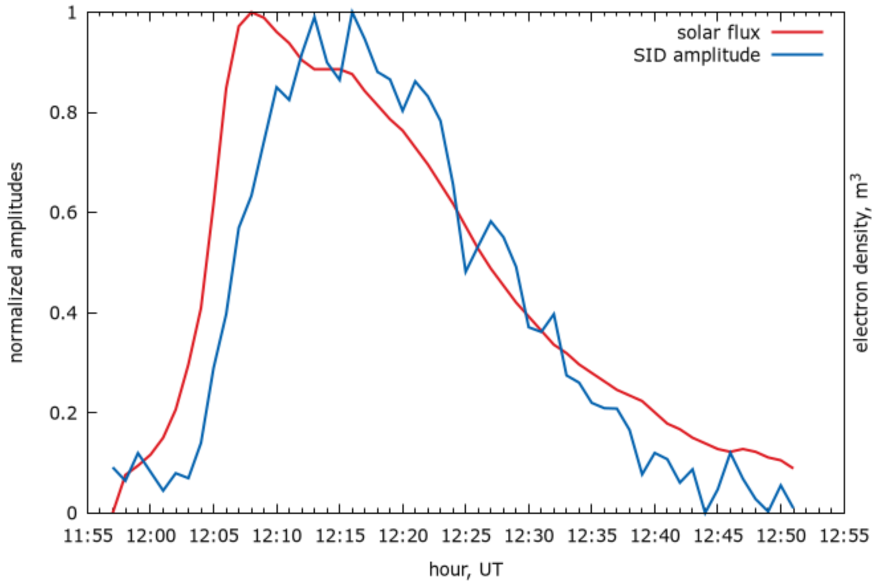

Figure 4: Normalized C-class solar flare amplitudes and the peak observed by the SID monitor on 2022-03-23.

However, additional parameters has to be taken into account in order to obtain a better quantification. Improvement of the observations can be obtained by evaluating the conditions for constructive interference depending on the current D-layer properties. This would require longer observations than we have at the present moment. This model will also allow to quantify the baseline amplitude of the SID measurements and normalize correctly the resulting flare peaks.

The lack of historical data can be compensated by detailed modelling of the D-layer electron density (section 5). The accuracy of this model will depend on the available primary spectrum data (e.g. energy flux) and the quality of the D-layer model (air pressure, temperature, composition, etc.). The electron density at a given instant then will depend on the rates of production by the incoming solar or gamma ray radiation and the rate of recombination. In Fig. 4 it is seen that the increase in the refracted wave from the D-layer has a delay of 8 minutes after the onset of the event. Subsequently, at the trailing edge of the flare flux the recombination rate becomes greater than the production and the SID amplitude drops faster than the flux intensity. The time intervals between the peak maxima and the intersection between the trailing edges on the normalised plot provides the necessary information to evaluate the rates of ionisation and recombination. This model will additionally require knowledge of the relation between the amplitude of the refracted wave and the electron density that will add additional degrees of freedom to the calculations. And finally, the amplitude will also depend on the amount of absorption of the incoming wave. In the case of GRB, this information will be not available due to the limitations of the space based detectors that would be saturated by the incoming high energy photons.

Gamma rays have energies orders of magnitude greater than the X-rays from the solar flares. This will make their attenuation and interaction more difficult and therefore the ionisation effects will be smaller. However, a significant contribution to the electron density and therefore the amplitude of the observed VLF wave can depend on secondary effects. The contribution of the secondary to the observed amplitudes are currently being modelled and investigated by the authors.

7. Conclusions

In this work we present an approach for quantification of solar flares observations with a sudden ionospheric disturbance(SID) monitor and discuss the possible common properties of these observations in the case of astrophysical events as gamma ray bursts. Two approaches were used - an empirical approach to directly relate the flare intensity to the observed by the SID monitor amplitude. The second approach was to evaluate the ionisation resulting from a known solar flare in order to obtain the amplitude of the refracted wave.

At this point, the lack of historical data limits the accuracy of the empirical observations. A better algorithm fro peak normalisation to remove the baseline values and a solar activity proxy (Ly-α) is necessary. Local station model will help quantify the observed amplitudes and relate them to the intensity of the solar flares. High class flares data then can be used to estimate the effect of astrophysical photon sources.

Modelling offers a more detailed control over the governing parameters but requires knowledge of the D-layer composition and physical parameters as well as a good theoretical model of the refracted amplitude as a function of the D-layer electron density.

This work will serve as a basis for further research and detailed modelling of the ionisation effects in the D-ionospheric layer. Successful quantification of the solar flare peaks observed with the SID monitor will be used for additional real-time evaluation of the magnitude and the impact of solar flares on the space weather conditions and radio communications.

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