# Natural and man-made terrestrial electromagnetic noise: an outlook

**Cesidio Bianchi and Antonio Meloni**

*Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*

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The terrestrial environment is continuously exposed to electromagnetic radiations which set up a «background» electromagnetic noise. Within the Non Ionizing Radiation band (NIR), *i.e.* for frequencies lower than 300 GHz, this background can have a natural or an artificial origin. Natural origins of electromagnetic radiations are generally atmospheric or cosmic while artificial origins are technological applications, power transmission, communications, etc. This paper briefly describes the natural and man-made electromagnetic noise in the NIR band. Natural noise comes from a large variety of sources involving different physical phenomena and covering a wide range of frequencies and showing various propagation characteristics with an extremely broad range of power levels. Due to technological growth man-made electromagnetic noise is nowadays superimposed on natural noise almost everywhere on Earth. In the last decades man-made noise has increased dramatically over and above the natural noise in residential and business areas. This increase has led some scientists to consider possible negative effects of electromagnetic waves on human life and living systems in general. Accurate measurements of natural and man-made electromagnetic noise are necessary to understand the relative power levels in the different bands and their influence on life.

**Key words** *radio noise – background noise*

## 1. Introduction

Natural electromagnetic noise sources existing since the origin of the Earth may be influencing the evolution of living systems. Understanding how this background noise is generated and distributed and how it interacts with living systems, can contribute to the general knowledge of life on Earth. In this review we consider the different frequency ranges, starting from the lowest frequencies generated within the ionospheric and magnetospheric cavities, up to the microwave band, including galactic noise, for both natural and man-made noise.

Different sources generate natural noise inside the magnetospheric cavity at different frequencies. A primary source of noise is given by the interaction of particles and waves coming from outer space with the magnetosphere plasma at various altitudes; another source is inside the ionospheric cavity where atmospheric lightning discharges produce several interesting propagating phenomena. At higher frequency radio noise originated in the atmosphere becomes less important and cosmic noise is prevalent up to the millimetric wavelength.

Human technologies implanted for power transmission and communications are the well known causes of man made noise. Man-made noise, mainly due to communication and broadcasting systems, electric energy transport systems, automotive ignition, industrial thermal processes and instruments for scientific/medical appliances is distributed, albeit not uniformly, in all bands. In VLF-HF band atmospheric noise is still larger than man-made noise in the order of a tenth of dB in rural areas and

*Mailing address*: Dr. Cesidio Bianchi, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy; e-mail: bianchi@ingv.it
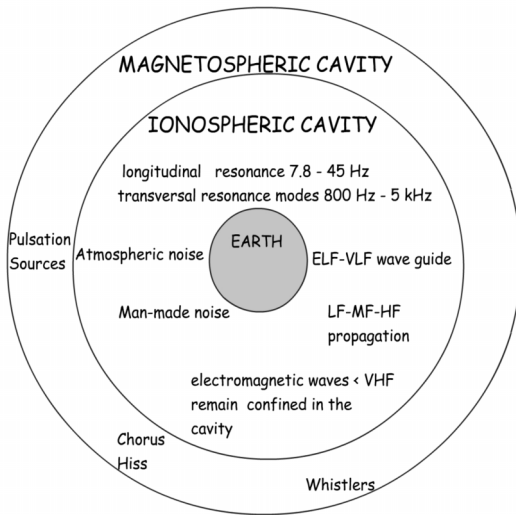
**Fig. 1.** A schematic representation of terrestrial natural and man-made radio noise sources within the magnetosphere-ionosphere system.

simply overcomes man-made noise in business areas. In general man-made noise is concentrated in particular frequencies in association with technological applications.

Both contributions, natural and man-made, affect technological applications such as communication, remote sensing, etc. The purpose of this work is to describe the electromagnetic terrestrial environment and the main sources of emission both natural and man-made. Figure 1 shows some propagation mode names and acronyms for natural contributions in the terrestrial environment inside the magnetosphere and ionospheric cavity.

## 2. Natural radio noise

Non Ionizing Radiation (NIR) electromagnetic waves range from the mHz to 300 GHz spanning over 14 orders of magnitude (table I). The corresponding wavelengths range from the dimension of the solar system, for waves around the mHz frequencies, to millimeters for frequencies around 300 GHz.

### 2.1. Magnetic noise in ULF/ELF band and other propagating phenomena

The Earth's magnetic field is not only static but also includes very slow time variations: secular, annual, 27 days, diurnal and substorm magnetic bay type variations at very low frequency (<1 mHz); all this can be considered a sort of «natural magnetic» noise. Variation amplitudes can be quantified in tenths of nT for the diurnal variation and hundreds, or exceptionally, thousands of nT in the case of strong magnetic storms (see Kivelson and Russell, 1995; Merrill *et al.*, 1998). At higher frequencies in this band various other phenomena, for example geomagnetic pulsations, take place. Geomagnetic pulsations, *i.e.*, Ultra-Low-Frequency (ULF) waves cover roughly the frequency range from 1 mHz to 1 Hz, *i.e.*, from the lowest frequency the magnetospheric cavity can sustain, up to the various ion gyrofrequencies (see for example: Hughes, 1994; Richmond and Lu, 2000). Pulsation frequency is considered to be «ultra» low when it is lower than expected plasma frequencies, like plasma frequency and the ion gyrofrequency. Geomagnetic pulsations were first observed in the ground-based measurements of the 1859 Great Aurora events (Stewart, 1861) and were subsequently studied in depth. It is well known now that lower frequency pulsations are generally related to the Kelvin Helmholtz instability that takes place at the magnetopause, and is generated by the solar wind interacting with the magnetosphere, or by upstream waves in the foreshock region. Table II reports geomagnetic pulsations' average intensity, frequency and other information (modified from Lanzerotti *et al.*, 1990).

Other electromagnetic phenomena in the ULF/ELF band are originated by particles impinging on the magnetosphere causing electromagnetic emissions that propagate inside the magnetosphere cavity. Chorus emissions and auroral hiss are two other relevant phenomena. Chorus emissions are among the most intense plasma waves in the outer magnetosphere that propagate as far as the Earth surface and are observed at intermediate invariant latitudes. Since these emissions occur in matching audible sound bands, a simple tuned radio receiver can

**Table I.** NIR frequency bands and the main natural radio noise sources.

| | Frequency range | Wavelengh (m) | Main natural radio noise sources | Environment |
|---|---|---|---|---|
| ULF (Ultra Low Frequency) | 1-3000 mHz | $3\times10^{11}$-$3\times10^{8}$ | Resonances in the magnetospheric cavity, interaction with particles of solar origin and radiative pressure with the magnetosphere | Magnetospheric cavity |
| ELF (Extremely Low Frequency) | 3-3000 Hz | $10^{8}$-$10^{5}$ | Resonances in the ionospheric cavity | Ionospheric cavity |
| VLF (Very Low Frequency) | 3-30 kHz | $10^{5}$-$10^{4}$ | Propagation in the ionospheric cavity of the atmospheric disharge radiate energy | Ionospheric cavity |
| LF (Low Frequency) | 30-300 kHz | $10^{4}$-$10^{3}$ | Atmospheric noise | Ionospheric cavity |
| MF (Medium Frequency) | 300-3000 kHz | $10^{3}$-$10^{2}$ | Atmospheric noise | Ionospheric cavity |
| HF (High Frequency) | 3-30 MHz | $10^{2}$-10 | Atmospheric and cosmic noise | Ionospheric cavity |
| VHF (Very High Frequency) | 30-300 MHz | 10-1 | Atmospheric and cosmic noise | Earth surfaces (mainly due to the cosmic noise that penetrates the ionospheric layers) |
| UHF (Ultra High Frequency) | 300-3000 MHz | 1-$10^{-1}$ | Cosmic noise | As above |
| SHF (Super High Frequency) | 3-30 GHz | $10^{-1}$-$10^{-2}$ | Cosmic noise | As above |
| EHF (Extremely High Frequency) | 30-300 GHz | $10^{-2}$-$10^{-3}$ | Cosmic noise | As above |

convert natural radio signals into sound. The Chorus spectral features (from 500 Hz to 1.2 kHz) consist in the succession of predominantly rising tones which resemble a chorus of chirping birds from which these emissions take their name. Auroral hiss emissions are broad, intense electromagnetic emissions which occur over a wide frequency range from a few hundred Hz to several tens of kHz occurring mainly in the auroral zone. This spreading at high frequencies is caused by the anisotropic character of whistler mode propagation (see later). The resulting tones are strongly modulated hiss-like tones.

**Table II.** Magnetic noise sources in the pulsation band.

| Pulsation classes | Continuous pulsations | | | | | Irregular pulsations | | |
|---|---|---|---|---|---|---|---|---|
| | Pc1 | Pc1 | Pc3 | Pc4 | Pc5 | Pi1 | Pi2 | Incoherent noise |
| Period (s) | 0.2-5 | 5-10 | 10-45 | 45-150 | 150-600 | 1-40 | 40-150 | 1-1000 |
| Frequency (mHz) | 200-5000 | 100-200 | 22-100 | 7-22 | 2-7 | 25-1000 | 2-25 | 1-1000 |
| Intensity (nT) | 1 | 3 | 10 | <300 | 300 | 10 | 100 | - |
| Source | Electromagnetic ion cyclotron instability in the equatorial magnetosphere | Electromagnetic ion cyclotron instability in the equatorial magnetosphere | Wave-particle interaction in the bow shock region | Drift of protons from the nightside | Magnetopause instability | Modulation of particles | Substorms | Ionospheric current (intensity increase with the magnetic activity) |

## 2.2. *Atmospheric noise in ELF/VLF band and related electromagnetic phenomena*

Lightning flashes are the main source of energy for the electromagnetic background inside the ionospheric cavity. Starting from the lower band ELF (few Hz) up to several VHF (hundreds MHz) the noise originates mainly from the energy radiated by lightning strokes (see for example: Cummer and Inan, 2000; Mika *et al.*, 2005). Several million lightning strokes occur daily from an estimated 2000 storms worldwide, and the Earth is hit about 100 times a second by lightning. The discharge is very violent and can easily reach 10000 A. The amount of energy released by each discharge can vary from units to tenths of GJ. Hence, for the duration of the discharge (less than 1 s), the power involved in this phenomenon is of the order of 1-10 GW. The annual total released energy is in the order of $10^{19}$ J. If only 10% of this energy is radiated as electromagnetic energy (fig. 2) it would be comparable to the energy produced in 1970 by the electric power stations in the world.

The main relevant phenomena in the ELF lower band are the Schumann resonances (Bliokh *et al.*, 1980; Sentman, 1987; Sentman,
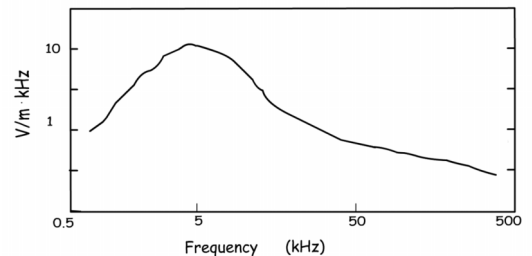
**Fig. 2.** Lightning frequency domain electromagnetic spectrum.

and Fraser, 1991). This phenomenon consists of a wide spectrum electromagnetic signal, composed by dumped waves of frequencies below 60 Hz. Schumann resonances occur because the Earth and the ionosphere form a natural wave guide that shows a fundamental resonance frequency at 7.8 Hz and upper harmonic components at about 15.6, 23.4 and 31.2 Hz (fig. 3). The Earth-atmosphere system can be seen, from an electromagnetic point of view, as a series of shell layers having different electrical conductivity with night-day asymmetry (Greifinger *et al.*,
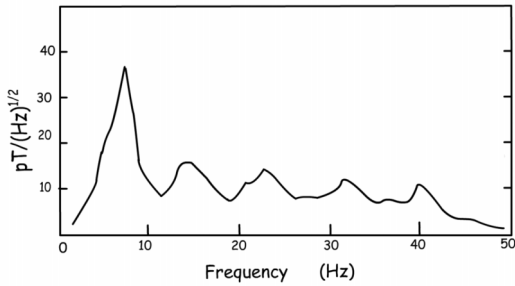
**Fig. 3.** Schumann resonance peaks.

2007). The Earth and the ionospheric layers appear as perfect conductors having air (of negligible conductivity) in between, forming an Earth-ionosphere cavity, in which electromagnetic radiation is trapped. Lightning strikes within the troposphere radiate energy into this system and the waves travel around the Earth. In the case of constructive interference, Earth-ionosphere cavity resonances are excited in the above mentioned frequency range (6-60 Hz).

ELF-VLF radio waves can propagate over long distances with small attenuation rates, typical 2-3 dB per Mm and phase stability. The propagation of ELF-VLF radio waves can conveniently be considered in a spherical earth surrounded by a concentric reflecting layer of electronic density into which VLF waves are launched and propagate. The propagation is controlled by the lowest region of the ionosphere. During the daytime this includes the lower $D$-region and, at night, the lowest part of the $E$-region. ELF VLF propagate for very long distances nearly without attenuation. As is well known, the phase and amplitude of VLF propagation can be described by an Earth-ionosphere waveguide (Davies, 1990). This description was exploited in past years for radio localization purposes (Swanson, 1983). The relation between the phase and height changes, over long distances, is given by

$$\Delta\varphi = -\frac{2\pi d\Delta h}{h\lambda}\left(\frac{h}{2a} + \frac{\lambda^2}{16h^2}\right) \qquad (2.1)$$

where $h$ is the mean height of reflection in the

$D$-region, $d$ the path length, $\varphi$ the phase, $\lambda$ the wavelength and $a$ is the Earth's radius (Budden, 1985; Wait, 1970). Phase shift can be expressed in degrees or in seconds by $\Delta t = \Delta\varphi\lambda/2\pi c$.

The amplitude of the electric field $E$ over long paths in a wave guide mode is approximately

$$E = -\frac{300e^{-ad}}{h}\left(\frac{p\lambda}{a\sin(d/a)}\right)0.5 \qquad (2.2)$$

where $\alpha$ is the attenuation rate and $p$ the radiated power (in kW). The signal amplitude is generally dependent on interferences of various propagation modes, that change with the variations of the wave guide parameters. Observation of the phase and amplitude of VLF waves were also used to study variability, morphology and other phenomena occurring in the low ionospheric region. Measurements and time-spatial statistical model is gven by Fieve *et al.* (2007), and Tomco and Hepner (2001).

Other relevant propagating phenomena in this frequency band are the so-called sferics, tweeks and whistlers. Radio atmospherics (or sferics for short, and sometime statics) are impulsive signals generated by lightning strokes that travel in the Earth-ionosphere wave guide. These impulsive signals (a few ms duration) propagate for thousands of kilometers. As in a real wave guide the Earth-ionosphere guide can sustain the propagation of these signals with very low attenuation values. Since only the upper part of the wave channel varies its position with time, the sferic propagation is determined by ionosphere conditions. Almost all AM receivers detect sferics as disturbances (sounds like pops and crashes). Sparks of lightning strokes are generally powerful sources of electromagnetic (radio) emission throughout the radio frequency spectrum from the very low radio frequencies up to the microwave frequency ranges and the visible light spectrum, even if the radio power is concentrated in VLF range from 0.1 to 10 kHz (fig. 4).

Tweeks are sferics dispersed in frequency. Their sound is similar to a bird's song usually in a frequency range of 1-7 kHz (fig. 5). When sferics propagate for long distances in a dispersive medium like the ionosphere their harmonic com-
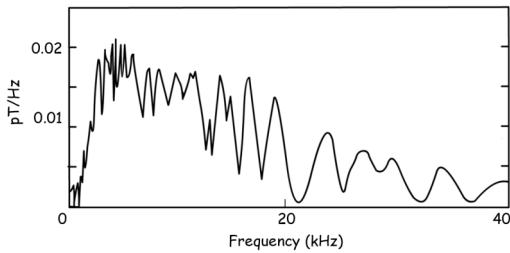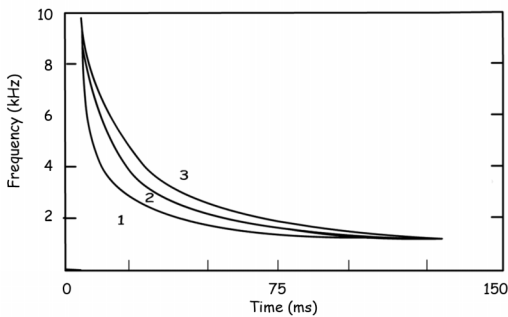
**Fig. 4.** Typical sferics frequency spectrum.



**Fig. 5.** Tweeks that traveled for different distances in the Earth-ionosphere waveguide. Shown for about 6000 km (1), 10 000 km (2) and 40 000 km (3) paths.
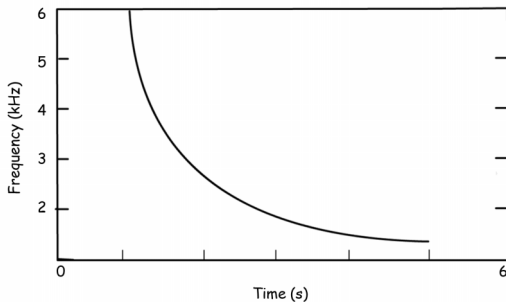


**Fig. 6.** Whistler spectrum.

ponents separate along the path (Helliwell, 1965). These components penetrate the ionosphere at various depths, in such a way that higher frequencies penetrate more than lower ones and as a consequence travel for longer distances. These different paths imply different arrival times at an ob-

server. In a spectrogram they appear as a descending tone with duration of the order of 25 to 150 ms. Tweeks are normally heard in the evening after sunset.

Whistlers are remarkable bursts generated by lightning discharge. When part of the discharge energy escapes the ionospheric barrier and propagates through the magnetosphere, whistlers can be heard in radio receivers as a relative long whistle decreasing in frequency, from about 6 kHz to a few hundred Hz (fig. 6). In the magnetosphere whistlers interact with free electrons and are forced to propagate along the Earth's magnetic field lines. The harmonic components of the signals identified as whistlers correspond to electromagnetic waves that have traveled several Earth radii arriving at different times to the observer. Lower frequencies are delayed 3-6 s with respect to the higher ones. The dispersion of a whistler depends on the length of the path over which the signal travels as well as the characteristics of the propagation medium such as its electron density (Kimura, 1989).

### 2.3. *Natural LF/MF/HF noise*

In this frequency range as well natural electromagnetic noise has its main source in the atmospheric electric discharges; noise amplitude is generally decreasing in intensity with frequency and is affected by ionospheric conditions. Since LF/MF/HF frequencies were very soon used in radio communications and broadcasting, in this frequency range natural radio noise has been the object of scientific studies in the radio engineers community. Natural LF/MF/HF noise radio measurements started very early as radio devices developed. The electromagnetic waves radiated by impulsive lightning discharges cannot escape the ionosphere border. Waves penetrate through the lowest ionospheric layers where they are variously absorbed, depending on frequency. Radio waves are reflected by the upper layers of the ionosphere up to a particular frequency, named 'critical frequency', that is dependent on local ionospheric condition. Moreover the incidence angle between the wave and the ionospheric layers plays an important role. In fact depending on the path geometry several propagating modes can be
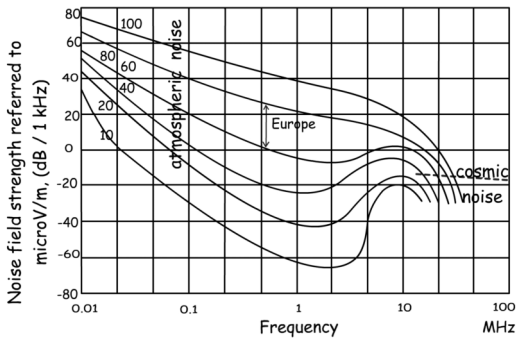
**Fig. 7.** Electric field strength *versus* frequency for atmospheric and cosmic noise.

established. The results are summarized in fig. 7 where the atmospheric noise *versus* frequency is plotted. The same figure shows cosmic noise at frequencies greater than ionosphere plasma frequency. The cosmic noise lowest frequency depends on the ionospheric conditions *i.e.* on electron plasma frequency about (15-30 MHz).

In the 1960s of last century a campaign of atmospheric noise measurement started by Consultative Committee International Radio (CCIR) gave the main contribution to the knowledge of background radio noise in the LF/MF/HF frequency range. Sixteen radiometers were installed worldwide and the results were summarized on report CCIR N.322 in 1964 (CCIR/ITU, 1964) and N.322-3 in 1988 (CCIR/ITU, 1988). The planetary atmospheric noise distribution is reported in fig. 7 where cosmic noise is also reported. In the figure the strongest levels are associated with the equatorial region and the weakest in Antarctica.

Many of these propagating phenomena, including the atmospheric noise diurnal variability, can be easily explained with simple considerations. In the LF-MF-HF range depending on frequency, waves penetrate relatively deeply into ionospheric plasma. Because of the non monotonic trend of the electron density with height, without considering the terrestrial magnetic field and collisions, each layer exhibits its own critical frequency up to the point where the normal incident angular frequency $\omega$ equals the angular plasma frequency $\omega_p$:

$$\omega = \omega_p = \sqrt{\frac{Ne^2}{\varepsilon_o m_e}} \qquad (2.3)$$

where, $N$ is the electron density local maximum, $e$ and $m_e$ are the charge and the mass of the electron, and $\varepsilon_o$ is the permittivity of free space. This gives a good approximate description of the confinement limits of waves inside the ionospheric cavity. The refractive phase index $\mu$ simple is

$$\mu = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} . \qquad (2.4)$$

This relation establishes the condition of penetration, for $\omega = \omega_p$ the refractive index $\mu$ is zero. To take into account the attenuation suffered by the radio waves, collisions between free electrons and neutral molecules, indicated with letter $\nu$, must be considered. In that case the phase refractive index $\mu$ becomes a complex quantity

$$\mu^2 = 1 - \frac{\omega_p^2}{\omega^2 \left(1 + \frac{\nu^2}{\omega^2}\right)} - \frac{j\omega_p^2 \left(\frac{\nu}{\omega}\right)}{\omega^2 \left(1 + \frac{\nu^2}{\omega^2}\right)} . \qquad (2.5)$$

The imaginary term is responsible for the absorption suffered by the radio wave during its propagation in the ionospheric plasma. In the lower ionospheric region, the attenuation rate $\alpha$ is relevant (up to 20 dB for each ionospheric hop). In fact $\alpha$ is proportional to the quantity $N\nu/\omega^2$ which reaches its maximum in the ionospheric $D$ layer. This seems in contradiction with the fact that waves of lower frequencies described in the relation (2.2) are less attenuated. This can be easily explained by relation (2.3), because of waves in ELF-VLF band do not penetrate deeply into the ionospheric plasma and therefore they are not absorbed. Terrestrial magnetic field and oblique incidence of the wave in the plasma are beyond the scope of this work. In the terrestrial surface the conditions of reflection and absorption are described by the reflection coefficient and the attenuation rate $\alpha$ and they are both dependent on the electric conductivity of the surface.

## 2.4. *Natural UHF/SHF/EHF noise*

In this frequency range the natural predominant noise is the background cosmic (or galactic) noise. In many ways cosmic noise is similar to terrestrial natural noise, like distant lightning strikes, or man-made radio noise; for this reason at the beginning of radio measurements it was difficult to identify the different sources. The discovery of the origin of this background noise is usually also marked as the birth of radio astronomy. In 1931 Karl Jansky built an antenna operating at 20.5 MHz and after months of careful observations he concluded that the source of the recorded noise was outside the solar system. Since then those frequency bands have been carefully investigated by radio astronomers (Kraus, 1988). In 1940 Grote Reber made the first radio map of our Milky Way galaxy at a frequency of 160 MHz. After that the radio emission from the Sun, Jupiter and other celestial bodies have been also identified by radio astronomers. Figure 8 reports the spectrum of solar and other main sources. Some of these sources are very strong or show a particular behavior (fig. 9). The synchrotron radiation has a characteristic wide spectrum like other impulsive radio sources. Moreover galactic or stellar systems generate a strong and common noise source: the thermal noise due to random motion of electrically charged particles in space. Thermal noise arises from electrons and ions in motion in a dissipative media. Others
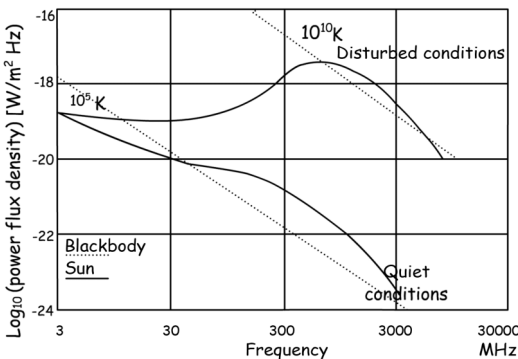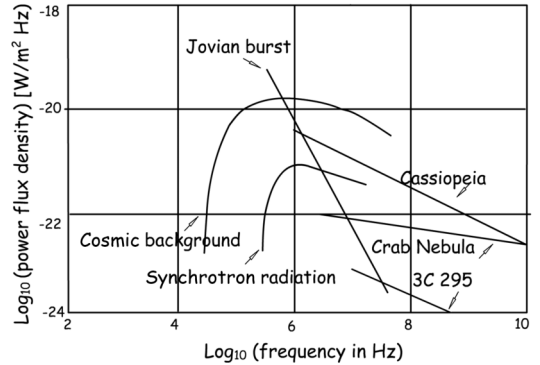


**Fig. 9.** Some sources of radio emissions and cosmic background.

sources are the bremsstrahlung radiation mainly due to electron proton collision (solar chromosphere, Orion nebula etc.).

The Earth is not the only planet that shows a large variety of radio signals. Almost all planets have an electromagnetic background, for instance Venus is quite similar to the Earth, and the four gas giants, Jupiter, Saturn, Uranus and Neptune are natural emitters of HF radio signals. Due to its huge atmospheric disharges Jupiter is one of the major radio emitters. The sun is the most powerful electromagnetic emitter in our solar system, able to generate very broadband radio emissions. In the solar radio emission, several phenomena like flares, magnetic waves, and storms of electrically charged nuclear particles and ions, directly cause and/or influence the propagation of electromagnetic waves throughout the known solar spectrum.

## 3. Man-made electromagnetic noise

Man-made noise is originated by human technologies. It is strongly dependent on the distance from the sources (power lines, radio, TV communication installations and other) which can be very variable, on frequency and on emitted power. Power and frequency in their time and spatial distribution are the quantities that best describe all man-made radio sources. Other important characteristics are the type of emitted waves, con-



**Fig. 8.** Solar radio emissions.

tinuous or impulsive, their modulation and wave polarization. Terrestrial man-made sources are mainly located in business, industrial and residential areas. In rural (countryside) and 'quiet rural' areas the sources become scarce (see for example report CCIR/ITU, 1990). In spite of its relevance, man made noise power, depending on frequency band, is on average 20-30 dB lower, in 'quiet rural' areas than the business and residential area (fig. 10). Of course, starting from the 1960's, satellite communication systems also contribute to man-made noise measurable on Earth.



**Fig. 10.** Median values of man-made radio noise power (solid lines) expressed in terms of $F_{am}$ (dB above thermal noise at $T_0$=288 K). Atmospheric noise (dashed lines) and cosmic background noise (dotted line) are reported for comparison with man-made noise.



**Fig. 11.** Power emitted by the most common communication systems.

As previously done for natural electromagnetic noise, the following man-made noise contributions are described in the diverse frequency bands with the indication of their main sources.

### 3.1. *ELF band*

In this band the strongest source of man-made noise comes from the electric power lines which operate ideally at a single frequency, generally 50 Hz (60 Hz in U.S.A.). The electric and magnetic fields generated at this frequency are practically decoupled and because of power lines' multi-polar configuration, decrease dramatically with the distance from the lines. The power lines are now spread over the planet in all continents except Antarctica where natural ELF waves close to 50-60 Hz can be recorded because there is a smaller amount of disturbance. Also, some uninhabited regions in other continents are relatively free from this kind of disturbance but in general, in the ELF band, the 50-60 Hz electric and magnetic fields are the strongest man-made source of noise both as emitted power and as extension of the source.
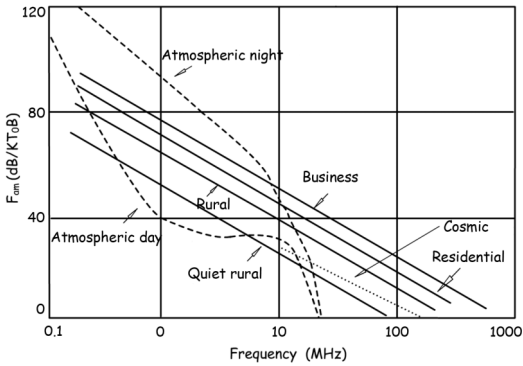
### 3.2. *VLF-HF band*

As in the case of other frequencies, man-made noise emissions are due to electronic devices for indoor use, industrial and radio communication apparatuses, including broadcasting radios, since all this equipment employs electrical oscillators that become unwanted sources of artificial radio emission.

The main localized sources are radio AM broadcasting (fig. 11) and some industrial equipment. Among the latter relevant sources are heaters that exploit magnetic induction and dielectric losses in the material. Other weaker but numerous sources, such as automotive ignition, heavily contribute to the background noise. We have also immeasurable indoor sources such as electrical household appliances, PC monitors TV, etc. Other scientific and medical devices are irrelevant in the background radio noise configuration in the considered range of frequency.
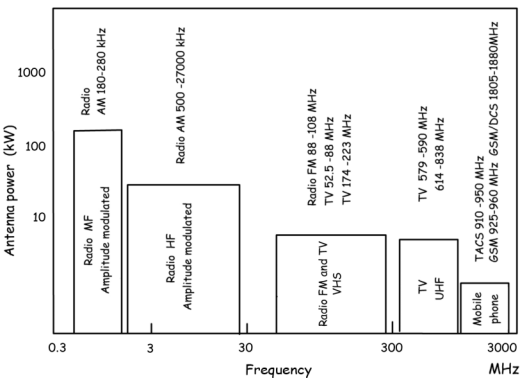
### 3.3. *VHF-UHF band*

Electromagnetic radiations in these bands are due to broadcasting FM radio TV and mobile phone service stations (fig. 11) and more important automotive ignition. Radar and satellite appliances do not make a very important contribution to background noise level. Main indoor sources are cordless phones, microwave, ovens, etc. This equipment does not make a significant impact outdoors.

### 3.4. *SHF-EHF band*

Because of the complexity of the system of radio communications and limitations in industrial applications operating at these frequencies, in this range only particular equipment is employed. These bands include satellite communication systems and survey, radar systems, scientific and medical appliances, for which there are intrinsic technological difficulties in manufacturing. For this reason man-made noise is very low in SHF and EHF bands. Moreover, their physical emission processes determine propagation modes for SHF and EHF waves which are strictly directional. Other technological applications in this range are related to passive observation and measurements as in radio astronomy.

## 4. Conclusions

This paper described the terrestrial natural electromagnetic noise and its main characteristics. Natural electromagnetic noise constitutes a background radio noise in which living systems are immersed and have consequently evolved since the origin of life on Earth. Superimposed on the natural background radio noise is man-made radio noise. The main man-made radio noise sources and its characteristics were also described and compared with the natural noise ones. Artificial noise levels have been constantly increasing in the last hundred years or so with the expansion of electromagnetic applications. A digression of the main characteristics, features and sources was made in the frequency range of non ionizing radiation.

A brief excursus of the natural radio sources was undertaken, starting from the lowest frequencies that the magnetosphere and ionosphere cavities can sustain, to the galactic and cosmic radio sources that penetrate the electronic density layers of the upper atmosphere. These studies started in the pioneer era of radio communication when the knowledge of natural noise was crucial for the assessment of an effective radio technology, have also revealed their relevance in geophysics, space physics, astrophysics and many other research fields over the years. In particular, a detailed knowledge of features of all natural electromagnetic waves in the magnetosphere is now imperative for ground based and satellite communication systems, but can also be relevant, for example, in the design of earth-orbiting and interplanetary spacecraft and in understanding how the background noise interacts with living systems.

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