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# Pectrum Sharing of VHF Data Exchange Satellite System

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**Abstract.** The Very High Frequency (VHF) Data Exchange Systems (VDES) addresses the need to protect Automatic Identification System (AIS) and provides essential digital communications contributions for e-Navigation and Global Maritime Distress and Safety System (GMDSS). As the satellite component of the VDES, VDE-SAT faces many technical challenges. Due to its global broadcasting nature, the signal emission of the newly added VDE-SAT satellite stations and its interference to the incumbent or future land mobile systems in shared bands is of a major concern in ITU spectrum allocation. This paper studies the existing regulations on the protection of the land mobile systems proposed by Electronic Communication Committee (ECC) and International Telecommunication Union (ITU) via the power flux density (PFD) concept. We infer the PFD masks from the two regulations and then show the corresponding impact on the VDE-SAT performance.

**Keywords:** maritime communications, VDE satellite system, spectrum sharing, power flux density (PFD), channel capacity.

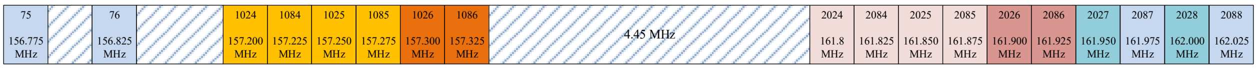
## 1. Introduction

In 2013, International Association of Lighthouse Authorities (IALA) put forward a Very High Frequency (VHF) Data Exchange System (VDES) initiative with the aim of offloading Automatic Identification System (AIS) and creating a new maritime communication channel powered by more spectrum-efficient technologies and higher capacity to support e-Navigation applications, and the modernization of the Global Maritime Distress and Safety System (GMDSS) [1].

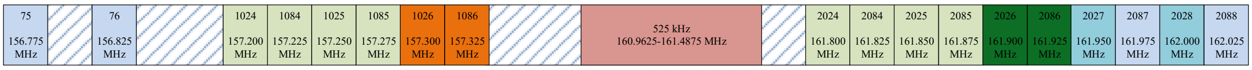
VDES consists of the existing AIS, Application Specific Message (ASM), as well as the new VHF Data Exchange (VDE) link which provides enhanced data exchange capacity on a global scale via transmitting and receiving data both terrestrially and with satellites. VDE further includes the terrestrial component (VDE-TER) to support high-density traffic in near-shore by building numerous shore stations and the satellite component (VDE-SAT) to provide access beyond Line of Sight at shore and unique communication access at high sea via low-earth orbiting (LEO) satellite, forming a space-ground integrated system and achieving global seamless coverage [2][3]. In addition, self-organized network is established to facilitate ad-hoc ship-to-ship communications. The ASM and VDE-TER frequency spectrum allocations have been approved in the World Radio-communication Conference organized by ITU in 2015 (WRC-15) [4] but the decision for VDE-SAT is postponed to WRC-19 due to the concerns for potential interference to incumbent land mobile services in that band.

Two frequency utilization plans for VDE-SAT under consideration are shown in Fig. 1 [5][6]. Both are within the frequency range of 156-162 MHz. Nevertheless, these bands are often used for conventional and trunked land mobile systems by safety agencies, utilities and transportation companies, e.g., police, fire, ambulance services, dispatched services such as taxis. Many businesses and industries throughout the world use land mobile service as their primary means of communication, especially from a fixed location to mobile users (i.e., from a base station to a fleet of mobile stations). Therefore, coordination between the VDE-SAT systems and the incumbent systems in shared bands is the main consideration at this stage.

(a) Existing channels



(b) VDE system frequency utilization plan 1



(c) VDE system frequency utilization plan 2

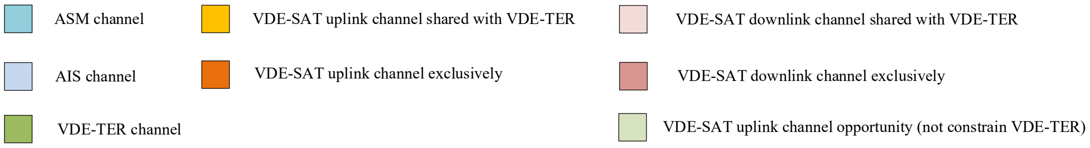


Fig. 1 VDES frequency utilization plans

## 2. Power Flux Density Masks

Emissions from different space stations may introduce co-channel interference into land systems. Unwanted radiation may enter from varying degrees, through the main beam and the side lobes of the land stations. While it is possible to calculate the interference from the emissions of one given space station on a single terrestrial system, it is an impractical task to calculate the cumulative interference effects from multiple space stations upon each of the large number of terrestrial systems in existence or yet to be implemented.

An effective solution to this issue is to place general restrictions on the emissions from the satellite stations to provide protection for terrestrial systems. The restrictions are expressed in terms of values of maximum allowed power flux density (PFD) emitted by any space stations to the surface of the Earth in a reference bandwidth under assumed free-space conditions. In other words, a PFD mask is provided to limit the emission energy of the space stations to minimize the harmful interference to the incumbent terrestrial systems.

To provide protection on the land mobile stations, constraints based on the field strength coordination threshold, or interference-to-noise ratio are commonly used for determining the impact of interference from the new systems. In this section, we focus on the implication of these constraints on the PFD mask that satellite stations need to comply with.

### 2.1 PFD Mask from ECC Recommendation T/R 25-08.

The Electronic Communications Committee (ECC) recommendation T/R 25-08 defines a coordination threshold for interference avoidance among land mobile systems from neighboring countries in the frequency band of 29.7 - 470 MHz [7]. For the frequency range proposed for the VDE-SAT downlink as shown in Fig. 1, the coordination threshold is $E_0 = 12\ \text{dB}(\mu\text{V/m})$ in 25 kHz. It translates to the PFD of

$$\Gamma_0 = \frac{{E_0}^2}{120\pi}, \tag{1}$$

where $120\pi\ (\Omega)$ the characteristic impedance of free space [8].

Since land station antennas are normally pointed in a nearly horizontal direction, where the receiver antenna gain is the peak gain $G_0$, then the corresponding input interference level $I_0$ is

$$I_0 = \Gamma_0 A_0, \tag{2}$$

where $A_0$ is the effective area of antenna, corresponding to antenna gain of $G_0$, and

$$A_0 = \frac{\lambda^2}{4\pi} G_0, \tag{3}$$

where $\lambda$ is the wavelength.

However, it should be noted that the coordination threshold from ECC Recommendation T/R 25-08 is determined based on that the receiver antennas are at near zero elevation angle, i.e., $\theta = 0^\circ$ to each other, where the gain $G_{\mathrm{Rx}}(0^\circ) = G_0$ is the maximum. As the angle of arrival of the interference increases, the radiation patterns of the land mobile station antenna provides increasing discrimination. Consequently, the PFD may be allowed to increase with the angle of arrival. In determining the extent of the allowable increase, due account has been taken of the characteristics of certain types of land mobile system antennas. This article refers to the following average side-lobe antenna pattern for both land base stations and mobiles as in [9]

$$G_{\mathrm{Rx}}(\theta) = \begin{cases} G_0 - 12 \cdot \left( \frac{\theta}{\theta_3} \right)^2 & 0^\circ \le \theta < \theta_3 \\ G_0 - 15 + 10 \cdot \log_{10}(k+1) & \theta_3 \le \theta < \theta_5 \\ G_0 - 15 + 10 \cdot \log_{10} \left( \frac{|\theta|}{\theta_3} )^{-1.5} + k \right) & \theta_5 \le \theta \le 90^\circ \end{cases}, \tag{4}$$

where $G_{\mathrm{Rx}}(\theta)$ is antenna gain relative to an isotropic antenna, $G_0$ is the maximum gain in the azimuth plane (dBi), $\theta_3 = 107.6 \cdot 10^{-0.1 \cdot G_0}$, $\theta_5 = \theta_3 \left( 1.25 - 1/1.2 \log_{10}(k+1) \right)^{1/2}$ and $k = 0.7$. Furthermore, Omnidirectional antennas with peak gain $G_0 = 8$ dBi and $G_0 = 2$ dBi are used to respectively represent the typical antennas of land base station and mobile station [10].

It can be summarized from above that land stations are capable of tolerating greater interfering PFD at angles other than 0° given the maximum amount of interference $I_0$ seen at the receiver, i.e., the PFD mask is

$$\Gamma^{\mathrm{E}}(\theta) = \frac{I_0}{A_{\mathrm{Rx}}(\theta)}, \tag{5}$$

which is plotted in Fig. 2 (a) for both cases of mobiles, $\Gamma^{\mathrm{E}}_{\mathrm{m}}(\theta)$, and base stations, $\Gamma^{\mathrm{E}}_{\mathrm{b}}(\theta)$. It is apparent that the case for mobiles is more stringent than the base stations, and hence the effective PFD mask $\overline{\Gamma}^{\mathrm{E}}(\theta)$ is $\Gamma^{\mathrm{E}}_{\mathrm{m}}(\theta)$. This is the maximum allowed PFD emitted by a VDE-SAT satellite to the surface of the Earth inferred from the ECC coordination threshold.

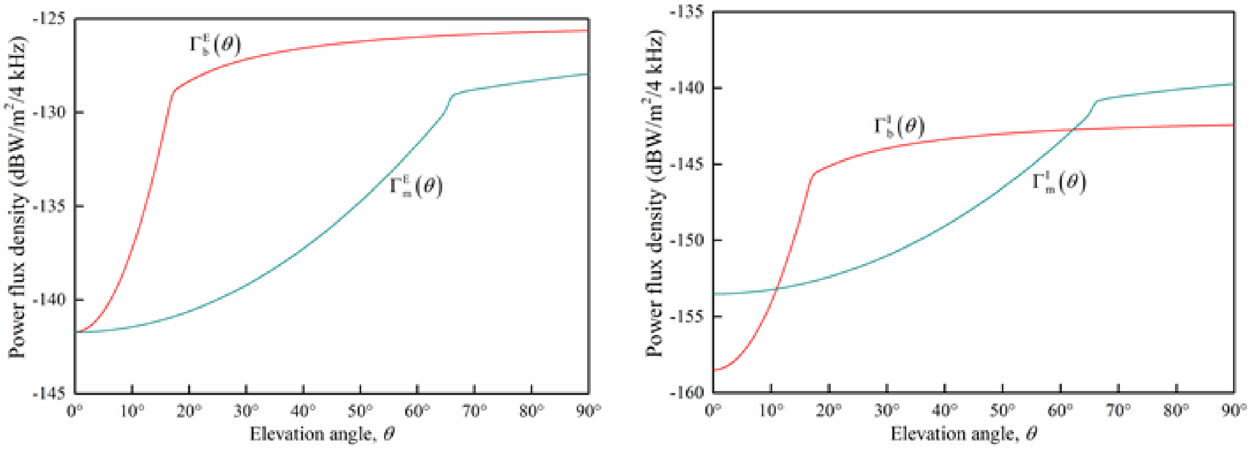
### 2.2 PFD Mask from Recommendation ITU-R M.1808.

The International Telecommunication Union (ITU) also defines an interference constraint in terms of the interference-to-noise ratio for protection of the conventional and trunked land mobile systems operating below 869 MHz band published in ITU-R M.1808 [10]. It indicates that a ratio of $I/N \le -6$ dB will not cause harmful interference to land mobile systems.

The land station thermal noise power $P_{\mathrm{N}}$ in linear form is

$$P_{\mathrm{N}} = \eta K T_0 B, \tag{6}$$

where $K = -198.6$ dBm/Hz/K is Boltzman constant, $T_0 = 290$ K is standard noise temperature, $B$ is receiver bandwidth, $\eta$ is receiver noise figure. Here, $B = 15$ kHz and $\eta = 7$ dB [10]. Noting that the system noise level $N$ consists of both internal and external noise. The internal noise is dominated by thermal noise in (6) with equivalent noise temperature of 30 dBK. For VDES frequency bands in the range of 156-162 MHz, man-made noise and galactic noise are the main sources of external noise. The noise temperature of man-made noise is 41 dBK, and that of galactic noise is $24\ \text{dBK}$ [11]. Thus, the overall noise temperature equals to the sum of the noise temperature of the three main noise sources and is $T = 41\ \text{dBK}$. The system noise level is then



(a) (b)

Fig. 2 Plot of PFD masks, $\Gamma_{\text{b}}^{\text{E}}(\theta)$ and $\Gamma_{\text{m}}^{\text{E}}(\theta)$, derived from the ECC coordination threshold, and PFD masks $\Gamma_{\text{m}}^{\text{I}}(\theta)$ and $\Gamma_{\text{b}}^{\text{I}}(\theta)$ derived from the ITU interference-to-noise constraint.

$$N = \kappa + T + B = -228.6\ \text{dBJ/K} + 41\ \text{dBK} + 42\ \text{dBHz} = -146\ \text{dBW}, \tag{7}$$

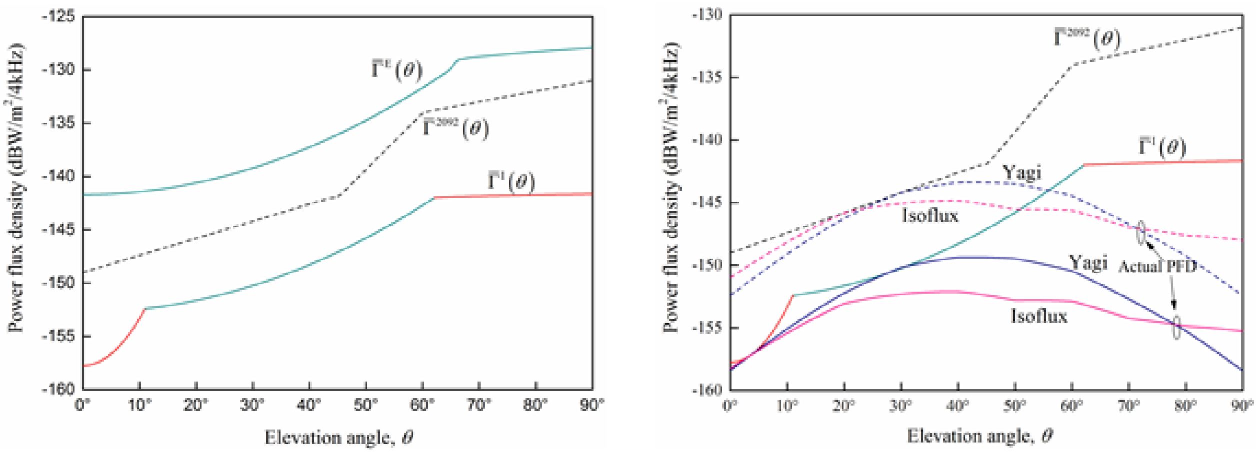
the maximum permissible power flux density $\Gamma^{\text{I}}(\theta)$ from VDE satellite is given by the following equation

$$\Gamma^{\text{I}}(\theta) = N + (I/N)_{\max} - A_{\text{Rx}}(\theta), \tag{8}$$

which is plotted in Fig. 2 (b) in $\text{dBW/m}^2$ per 4 kHz for both mobiles, $\Gamma_{\text{m}}^{\text{I}}(\theta)$, and base stations, $\Gamma_{\text{b}}^{\text{I}}(\theta)$. The ultimate maximum allowed PFD $\overline{\Gamma}^{\text{I}}(\theta)$ emitted by a VDE-SAT satellite to the surface of the Earth implied by the ITU interference-to-noise ratio constraint is the minimum one of $\Gamma_{\text{m}}^{\text{I}}(\theta)$ and $\Gamma_{\text{b}}^{\text{I}}(\theta)$, which is plotted in Fig. 3 (a) together with the ECC mask $\overline{\Gamma}^{\text{E}}(\theta)$.

## 3. VDE-SAT Link Budget

In order to ensure that there is no harmful interference caused by the satellite downlink on non-maritime terrestrial services sharing the same frequency (ensuring in-band carrier-to-interference requirement of terrestrial service receivers), [4] proposes a preliminary PFD mask which is shown in Fig. 3 (a), together with the two derived PFD masks $\overline{\Gamma}^{\text{E}}(\theta)$ and $\overline{\Gamma}^{\text{I}}(\theta)$. It can be seen that the preliminary PFD mask falls within ECC PFD mask but exceeds the derived ITU PFD mask.



(a) (b)

Fig. 3 (a) Comparison of PFD masks, i.e., $\overline{\Gamma}^{\mathrm{E}}(\theta)$ and $\overline{\Gamma}^{\mathrm{I}}(\theta)$ (solid curves) inferred from two constraints and the preliminary PFD mask $\overline{\Gamma}^{2092}(\theta)$ (dashed curves) from [4]. (b) For both cases of Yagi and Isoflux antennas, the actual PFD $\Gamma(\theta)$ (dashed curves) from [4] and the constrained PFD by ITU PFD mask (solid curves).

The power flux density can be expressed in mathematical form as

$$\Gamma(\theta)=\frac{P_{\mathrm{Tx}}G_{\mathrm{Tx}}(\theta)}{4\pi d(\theta)^2}, \tag{9}$$

where $P_{\mathrm{Tx}}$ is the transmit RF power of satellite, $G_{\mathrm{Tx}}(\theta)$ is satellite antenna gain, $d(\theta)$ is the slant range between the satellite and receivers at $\theta$ elevation angle.

Due to the frequencies used, it is likely that VDE-SAT will consist of low-earth orbiting (LEO) or medium-earth orbiting (MEO) satellites. In [4], a Low Earth Orbit (LEO) satellite with 600 km altitude is considered to present typical example of VDE satellite downlink solutions. With a LEO satellite at an altitude of $h=600\ \mathrm{km}$, the slant range $d(\theta)$ is calculated by

$$d(\theta)=\left((R+h)^2+R^2-2R(R+h)\sin(\theta+\alpha)\right)^{1/2}, \tag{10}$$

where $R$ is the radius of the Earth and $\alpha$ is the satellite's nadir offset angle, $\alpha$ is related to $\theta$ via

$$\alpha=\arcsin\left(\frac{R}{R+h}\cos(\theta)\right). \tag{11}$$

Furthermore, given the Yagi and Isoflux satellite antennas patterns $G_{\mathrm{Tx}}(\theta)$ as in [4], the maximum allowed transmit RF power of satellite can be calculated via (9) in order to satisfy

$$\Gamma(\theta)<\overline{\Gamma}^{2092}(\theta). \tag{12}$$

Through the check, a transmit RF power of $-12.4\ \mathrm{dBW}$ in 25 kHz will exactly ensure compliance with $\overline{\Gamma}^{2092}(\theta)$ with the satellite Yagi antenna pointed at the horizon, and $-5\ \mathrm{dBW}$ for Isoflux antenna. Similarly, A transmit RF power of $-18.5\ \mathrm{dBW}$ in 25 kHz will ensure compliance with $\overline{\Gamma}^{\mathrm{I}}(\theta)$ for Yagi antenna, and $-12.2\ \mathrm{dBW}$ for Isoflux antenna. That means a 6 dB and 7 dB back-off in PFD or Equivalent Isotropically Radiated Power (EIRP) are needed for Yagi antennas and Isoflux antennas respectively in order to comply with the ITU PFD mask. The derived actual power flux density via (9) is shown in Fig. 3 (b). To study the effects on VDE-SAT, we analyze the channel capacity as a result of the constrained PFD.

Given the PFD in (9), the received power by a ship is then

$$P_{\mathrm{s}}(\theta) = \Gamma(\theta) \cdot A_{\mathrm{s}}(\theta) = \Gamma(\theta) \cdot \frac{\lambda^2}{4\pi} G_{\mathrm{s}}(\theta), \tag{13}$$

where $G_{\mathrm{s}}(\theta)$ is the VHF antenna gain of the ship given in [4]. The corresponding received signal-to-noise ratio is thus

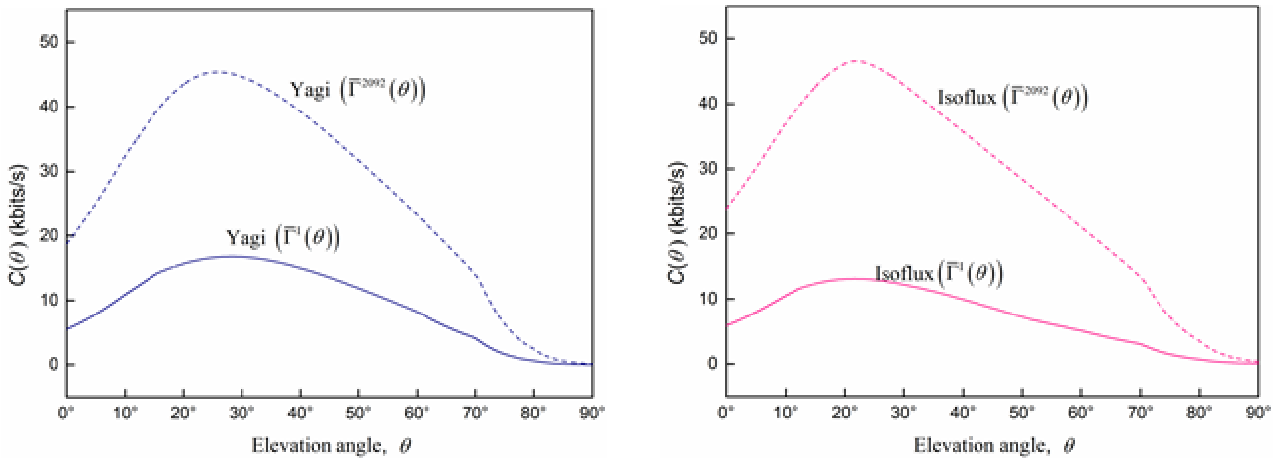
$$\rho_{\mathrm{s}}(\theta) = \frac{P_{\mathrm{s}}(\theta)}{\kappa T_{\mathrm{s}} B}, \tag{14}$$

where $T_{\mathrm{s}} = 30\ \mathrm{dBK}$ is the receiver noise temperature of the ship [4], and $B = 25\ \mathrm{kHz}$ the VDE-SAT channel spacing. Hence, the VDE-SAT channel capacity is determined by

$$C(\theta) = B \log_2\left(1 + \delta \rho_{\mathrm{s}}(\theta)\right),\ \theta \in \left[0^{\circ},\ 90^{\circ}\right], \tag{15}$$

which is plotted in Fig. 4, where $\delta = -6\ \mathrm{dB}$ is included to reflect the performance deficit between a realistic system and the theoretical limit.

It is observed from Fig. 4 that the channel capacity of VDE-SAT for both Yagi antenna and Isoflux antenna falls below 20 kbits/s in order to satisfy the PFD mask corresponding to the ITU interference to noise ratio, and is much less than the theoretical channel capacity calculated based on the preliminary PFD mask from [4]. It is thus evident that the ITU constraint has a great impact on the VDE-SAT channel capacity, which may pose difficulty in supporting vast e-Navigation applications.



(a) (b)

Fig. 4 Illustration of the channel capacity $C(\theta)$ calculated on the basis of the actual PFD (dashed curves) from [4] and the constrained PFD (solid curves) by ITU PFD mask for both cases of Yagi and Isoflux antennas.

## 4. Summary

In this paper, we study the maximum allowed interference emitted by VDE-SAT satellite to the incumbent land mobile systems in the VHF frequency band from 156 MHz to 162 MHz. To be specific, we investigate two regulations, i.e., the interference field strength threshold by ECC and the interference to noise ratio by ITU. We derive the corresponding PFD masks and analyze their implications on the VDE-SAT system. We have found that the ITU constraint corresponds to a more stringent PFD mask than ECC, thereby provides a better protection on the incumbent land mobile systems, however, imposes a profound limit on the system channel capacity, which may pose challenges to the implementation of e-Navigation and GMDSS. Frequency Plan 2 thus may seem to be necessary to compensate for the shortcoming in channel capacity due to the constrained EIRP.

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