Effects of artificial D-region disturbances on the transionospheric propagation of VLF waves

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Intense high-frequency (HF) electromagnetic radiation from ground-based facilities, as well as intense VLF radiation from Navy transmitters, heat the D-region of the ionosphere, modifying the electron-neutral collision frequency. The disturbed region scatters the VLF and ELF electromagnetic waves which propagate in the Earth-ionosphere waveguide and originate due to both human activities (from VLF transmitters) and natural phenomena (i.e., sferics emitted by lightning). We apply the recently developed Stanford FWM (full-wave method) model to the calculation of Born approximation scattering of the waveguide VLF and ELF waves by such ionospheric disturbances. The scattered waves are emitted both into the Earth-ionosphere waveguide and into the ionosphere. The waves scattered into the waveguide can be detected as perturbations in VLF signal amplitude and phase by ground-based VLF receivers located in the "shadow" of the D-region disturbance, i.e., at positions such that the great-circle path from the source to the receiver goes through (or close to) the disturbance. The waves scattered upward into the ionosphere propagate in the form of whistlers in a relatively narrow (i.e., of the horizontal size of the disturbance) "column" in the direction between the vertical and the geomagnetic field. These waves contribute to the electromagnetic radiation environment of the ionosphere and magnetosphere, and can be detected by satellites as enhancements of sferic radiation and narrowband VLF radiation from transmitters in the vicinity of powerful HF heaters and different-frequency VLF transmitters. Preliminary theoretical analysis shows that during HF heating by HAARP, the narrowband VLF enhancements inside the whistler "column" may significantly exceed the background which is due to VLF waves leaking into ionosphere from the waveguide in horizontally-stratified undisturbed ionosphere. Moreover, there are also perturbations in the "shadow" region of the disturbance, due to the scattered waves entering the ionosphere after being first reflected from the ground. Although much smaller than the radiation in the whistler "column", when expressed in dB, these "shadow" region perturbations are of the same order as the amplitude perturbations seen by the ground-based VLF receivers, and also may be detectable by satellites.