Optimized beam-painting as a more efficient alternative to geometric modulation for ELF/VLF wave generation

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Time-of-arrival (TOA) analysis is applied to observations performed during ELF/VLF wave generation experiments at the High-frequency Active Auroral Research Program (HAARP) observatory in Gakona, Alaska. ELF/VLF waves generated using amplitude modulation (AM) are compared with those generated using one type of geometric modulation (GM): "circle sweep." The GM format is combined with pulse modulation to control the physical area of the ionospheric ELF/VLF source region, effectively producing a beam-painting style of modulation. As a result, we are able to identify an optimal GM sweep length that maximizes the ELF/VLF signal amplitude received on the ground and simultaneously increases the HF-to-ELF/VLF conversion efficiency. The higher ELF/VLF signal amplitudes generated using GM (compared to AM) are quantified and systematically attributed to the area of the ELF/VLF source region, the effects of oblique HF heating, the effective duty cycle of the GM sweep, and the phased-array nature of the distributed ELF/VLF source region. The area of the ELF/VLF source region is identified as the most important characteristic that controls the received ELF/VLF amplitude, while the oblique HF heating angle employed produces a secondary effect. The low effective duty cycle of the GM sweep is the factor most detrimental to the received ELF/VLF amplitude, while the phased-array nature of the distributed source region serves to either increase or decrease the received ELF/VLF amplitude, depending on the ELF/VLF frequency and observation location. Based on these results, we suggest new modulation formats that are predicted to produce higher ELF/VLF amplitudes than the GM formats considered here. We conclude that an optimized "beam-painting" format can produce larger ELF/VLF signal amplitudes with higher HF-to-ELF/VLF conversion efficiency than "circle sweep" geometric modulation.