Experimental Observations of ELF/VLF Wave Generation Using Optimized Beam-Painting

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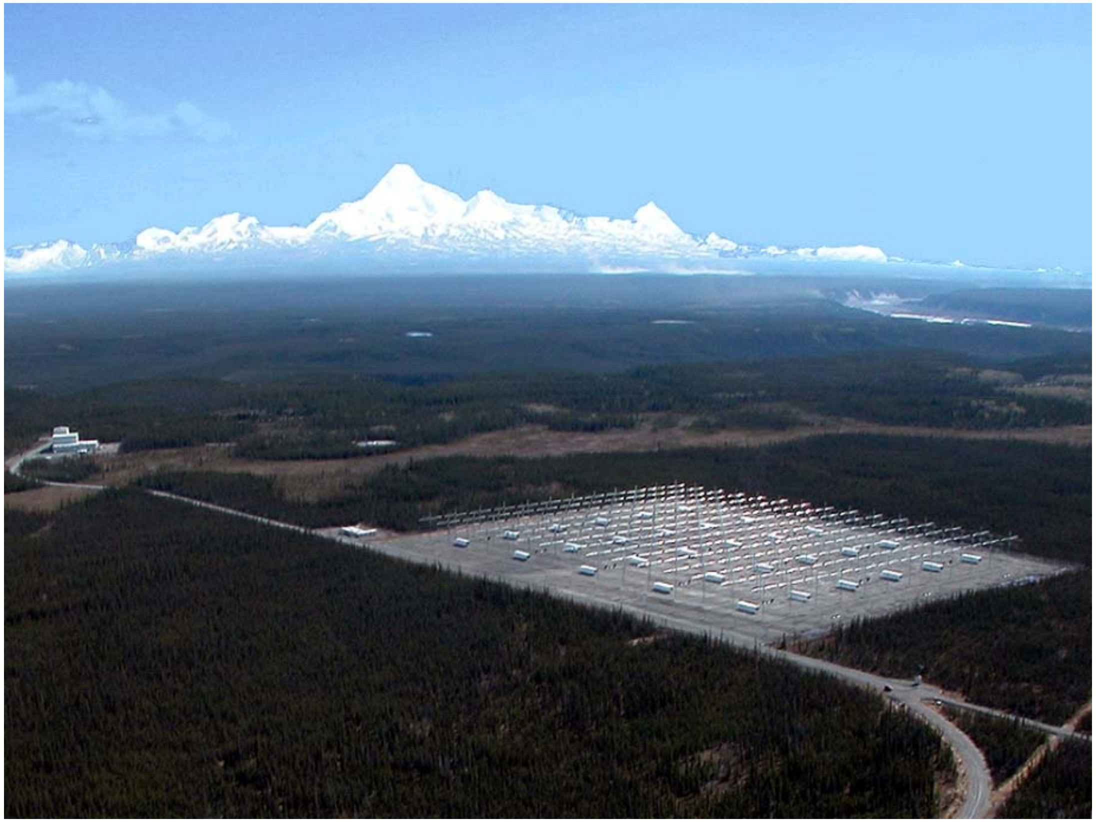
Overview

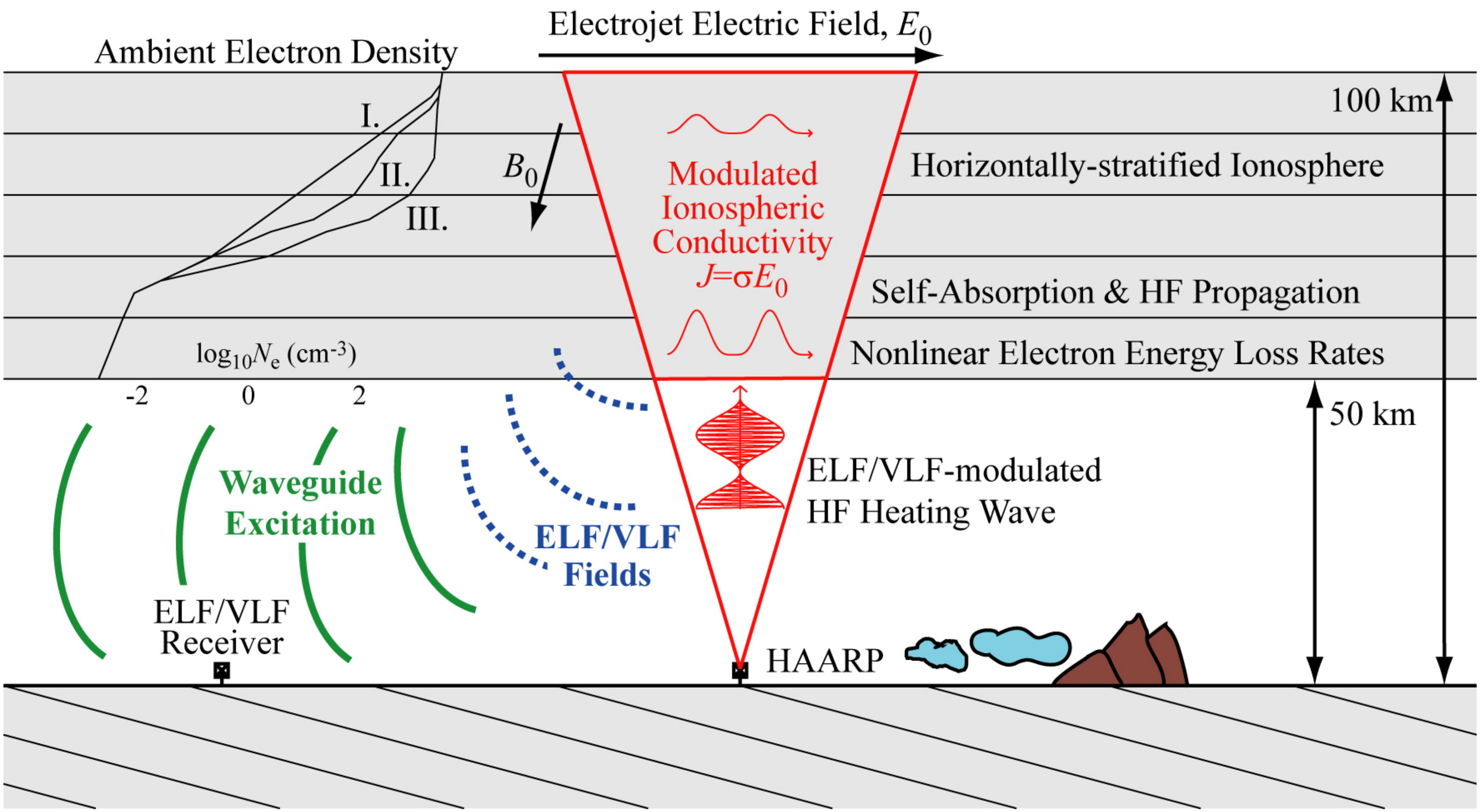
- Introduction to ELF/VLF wave generation and experiment description
- Beam-painting and geometric modulation
- Optimizing/Controlling the ELF/VLF Source
- Experimental Observations
- Summary

HAARP HF Transmitter

- High-frequency Active Auroral Research Program (HAARP)
- Phased Array (12x15) Transmitter
- 2.8 MHz – 10 MHz
- 3.6 MW Radiated Power
- 300 – 1000 MW ERP



ELF/VLF Wave Generation



Model Description

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

$$\nabla \cdot \vec{D} = \rho$$

$$\nabla \cdot \vec{B} = 0$$

$$\frac{\partial}{\partial t}\vec{J}_s = \frac{q_s^2 N_s}{m_s}\vec{E} + \frac{q_s \mu_0}{m_s}\vec{J}_s \times \vec{H} + q_s N_s \vec{g} - \nu_s \vec{J}_s$$

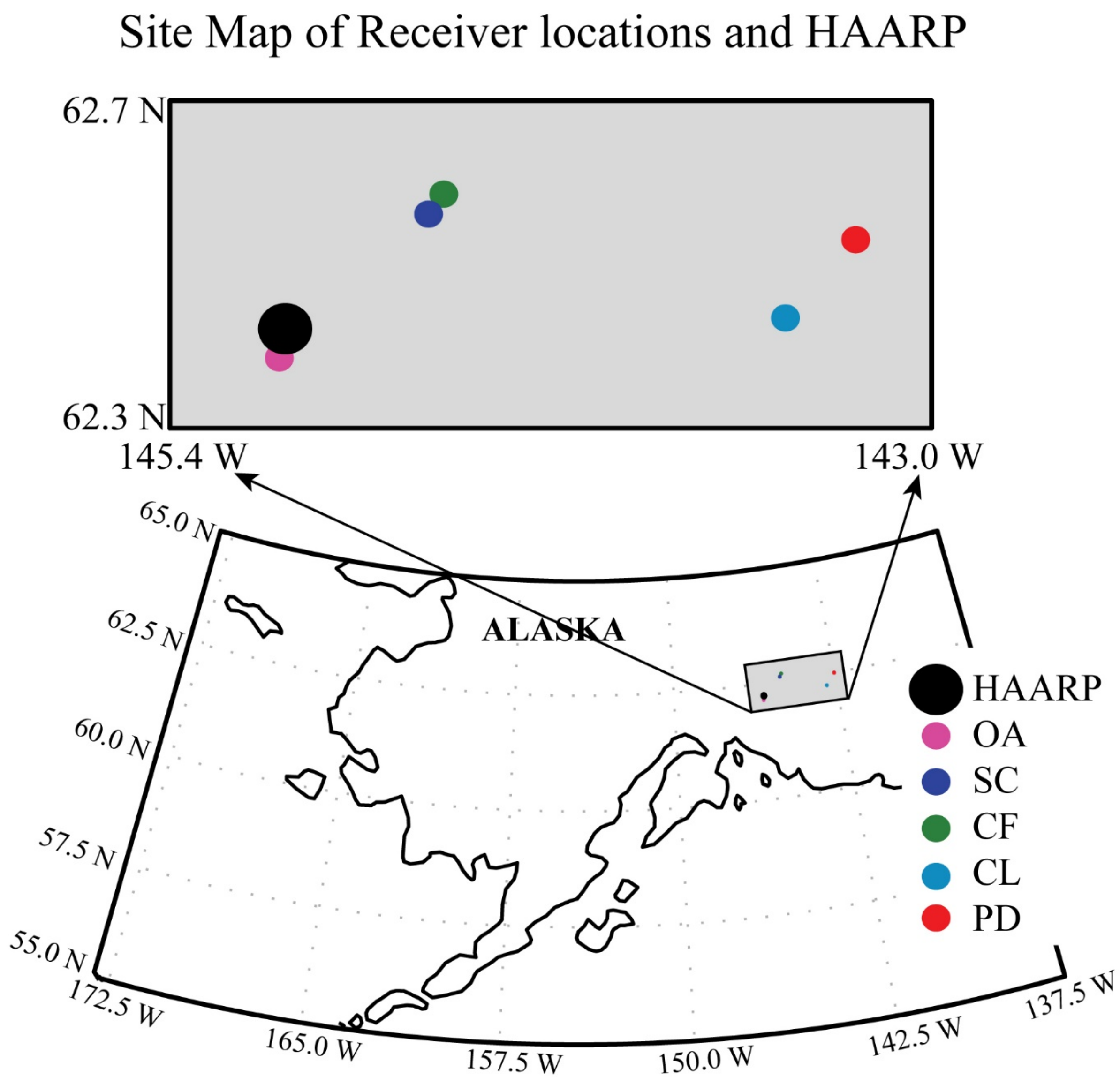
$$\frac{3}{2} N_s \kappa_B \frac{\partial T_s}{\partial t} = \vec{J}_s \cdot \vec{E} - \frac{3}{2}\kappa_B T_s \left.\frac{\partial N_s}{\partial t}\right|_{coll} - L(N_s, T_s, T_{s0})$$

- Maxwell's Equations coupled with the 1st and 2nd-order moments of the Boltzmann Equation
- Nonlinear coupling at JxH, vJ, and J*E
- Requires "harmonic balance" to provide tractable solutions

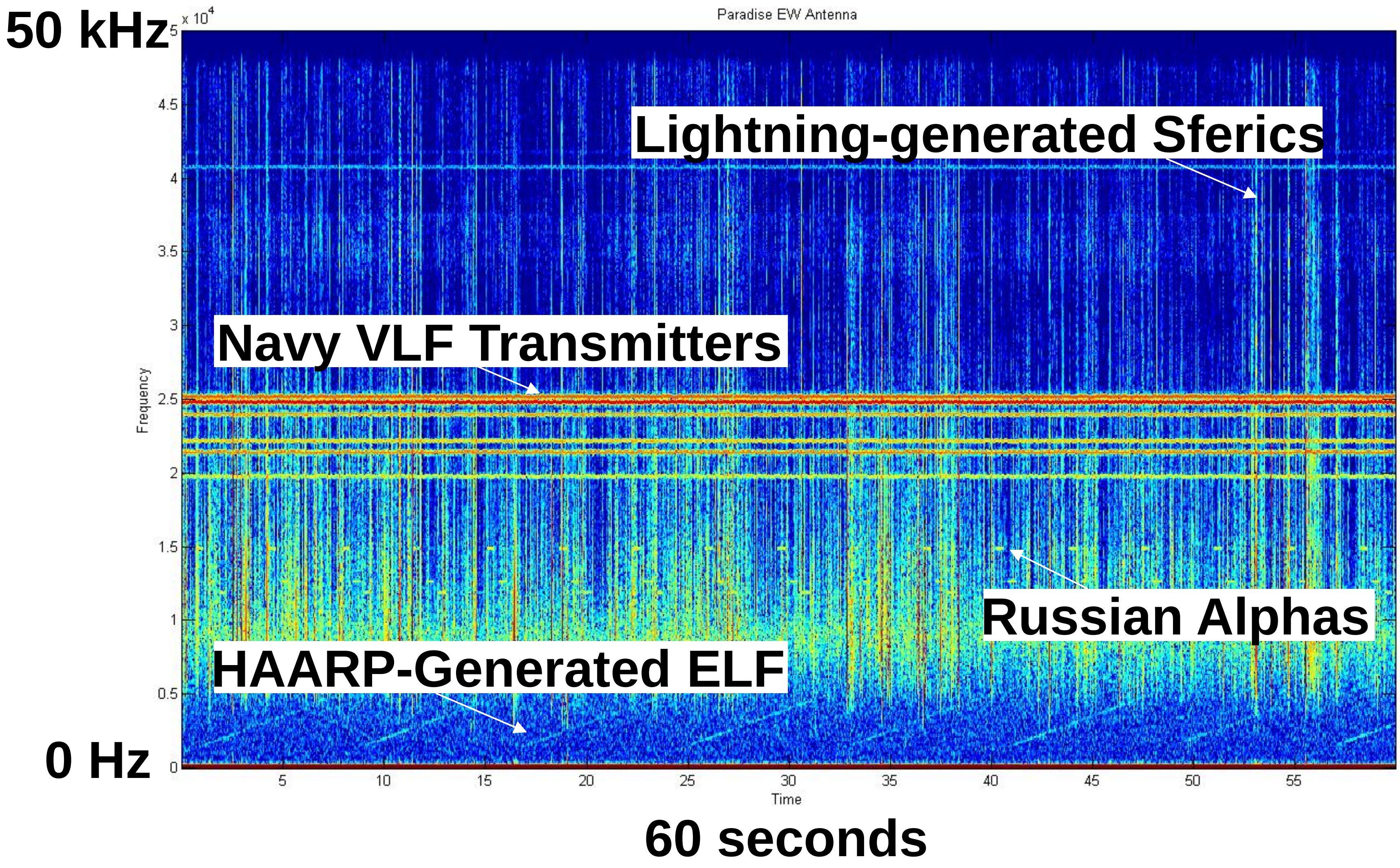
Antenna Winding

Receiver Locations

- Use HAARP to modulate the electrojet currents
- Perform low-ELF, ELF/VLF, and HF observations



Sportsmen's Paradise ELF/VLF Observations

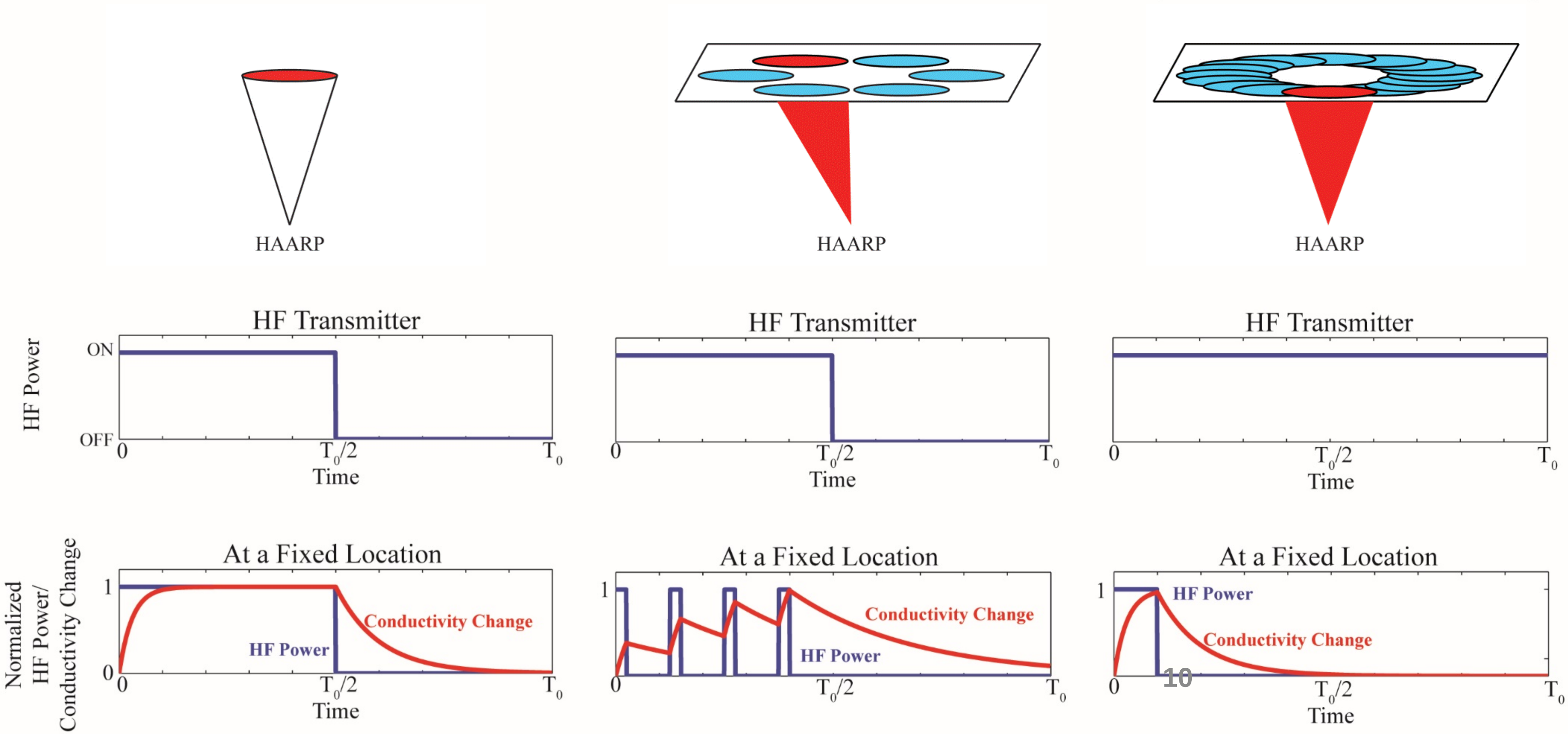


Beam Painting and Geometric Modulation

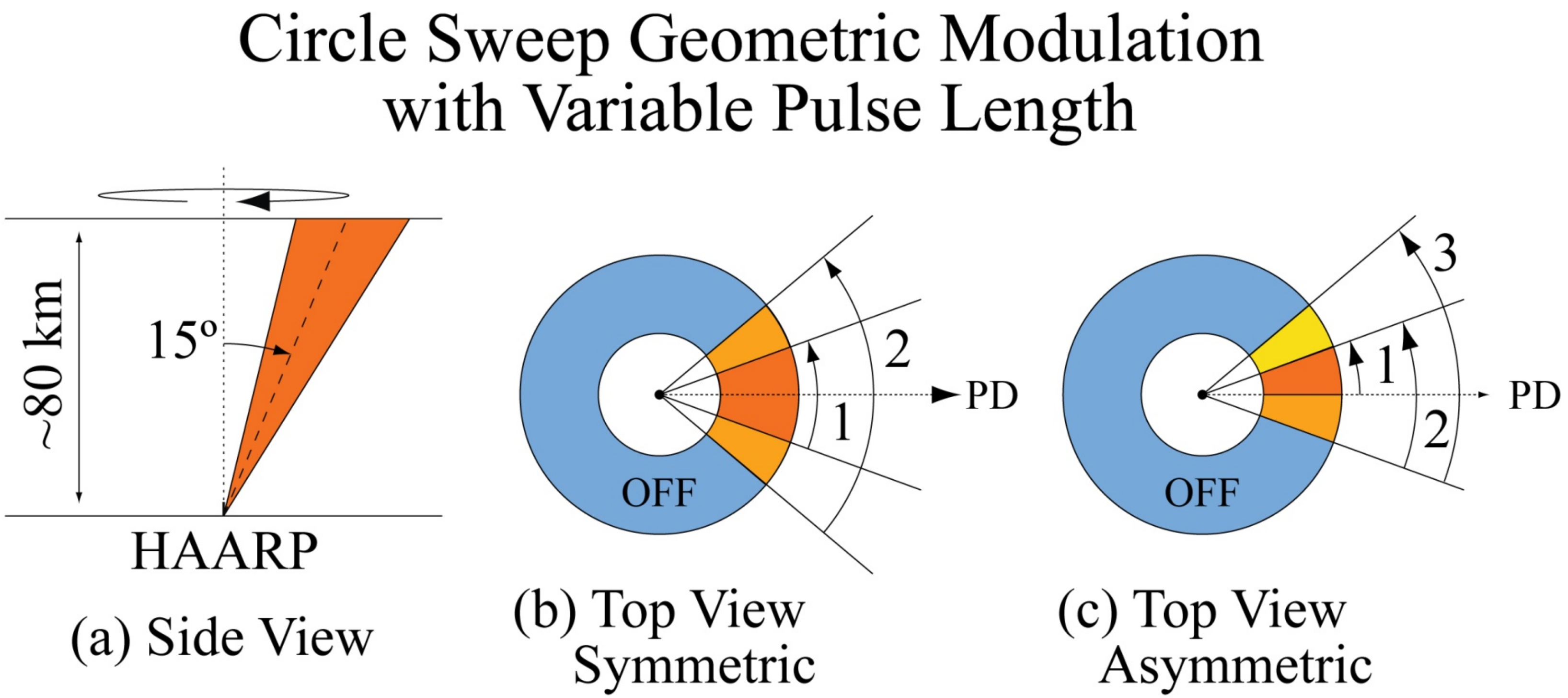
Past Work

Goal: To increase amplitudes of ELF/VLF wave generation

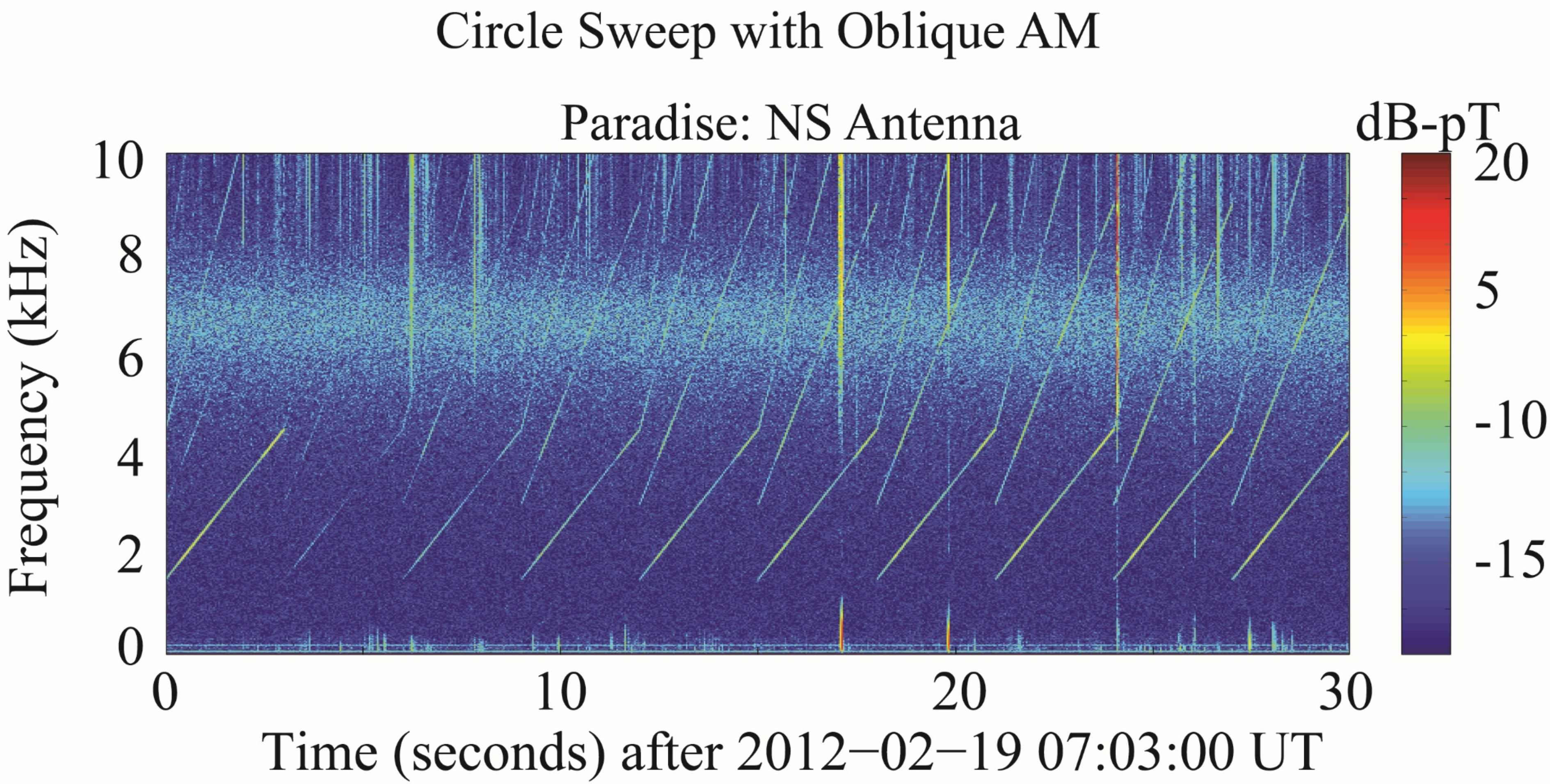
Amplitude Modulation	**Beam Painting** [*Papadoplous et al.*, 1989, 1990, *Barr et al.*, 1999]	**Geometric Modulation** [*Cohen et al.*, 2008, 2010a,b]



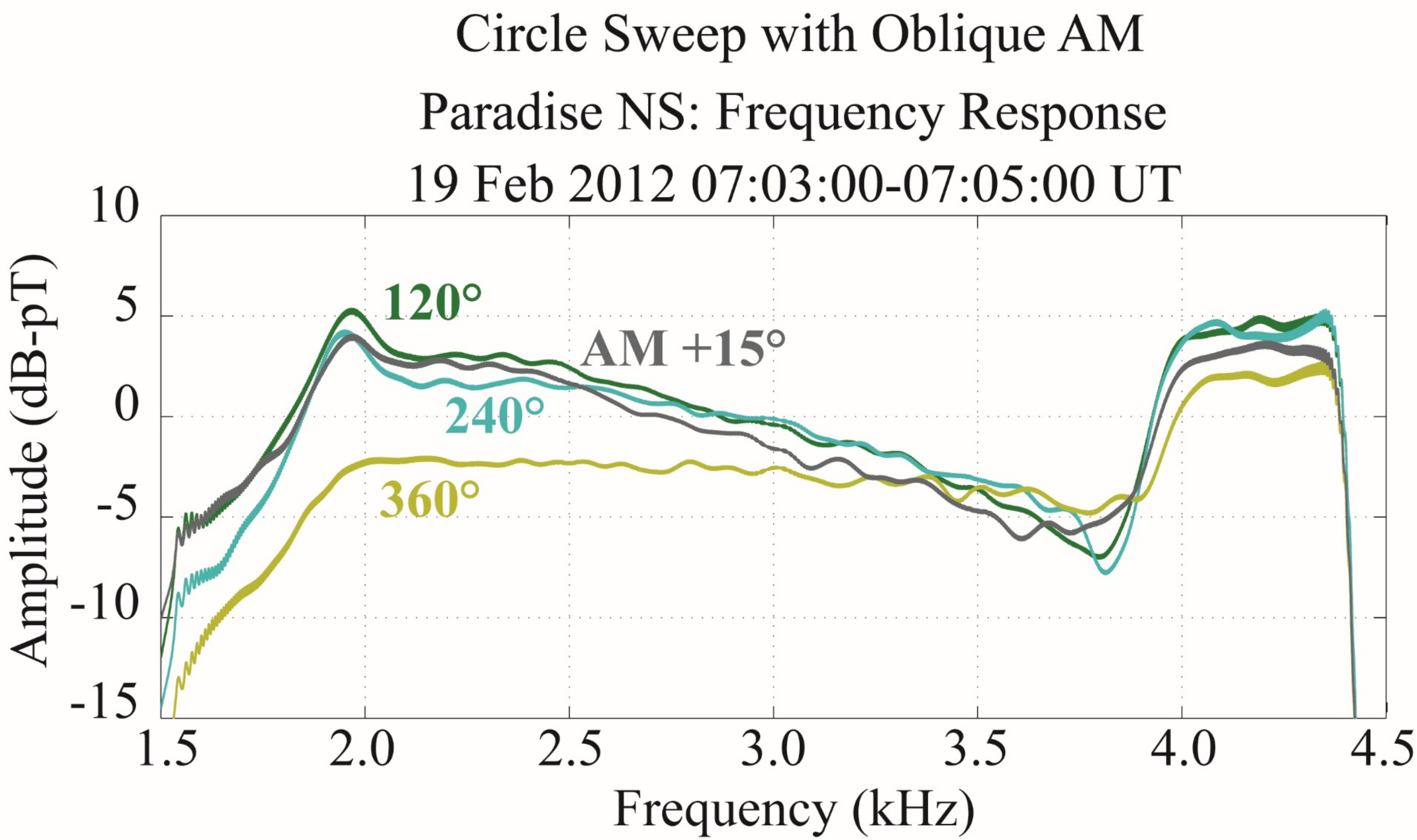
Geometric Modulation (GM) Variable Arc Length



BP/GM Spectrogram



BP/GM Frequency Response



GM Observed at Paradise

$$A_v \cdot \frac{A_o}{A_v} \cdot D_{GM} \cdot \frac{S_{GM}}{S_o} \frac{\sum_{i=1}^{N} A_i}{N \max(A_i)} \frac{\left|\sum_{i=1}^{N} A_i e^{j\phi_i}\right|}{\sum_{i=1}^{N} A_i} = \left|\sum_{i=1}^{N} A_i e^{j\phi_i}\right|$$

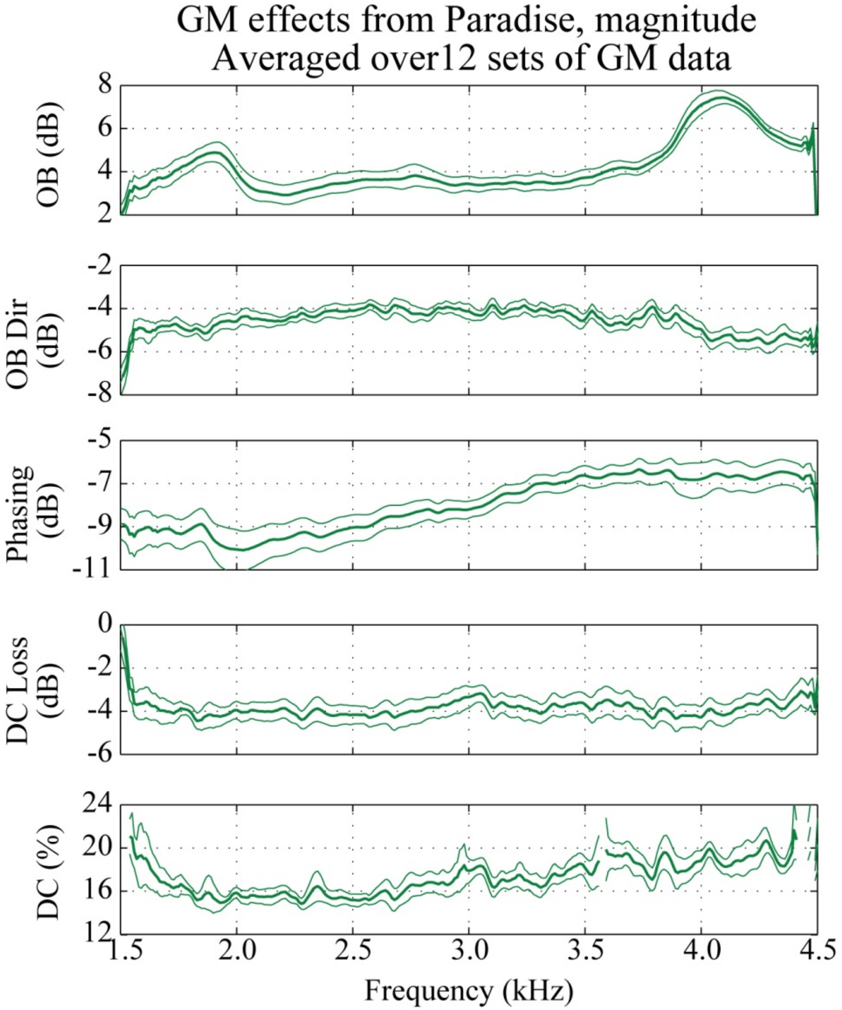
$\frac{A_o}{A_v}$ - Obliqueness

$\frac{\sum_{i=1}^{N} A_i}{N \max(A_i)}$ - Oblique Directionality

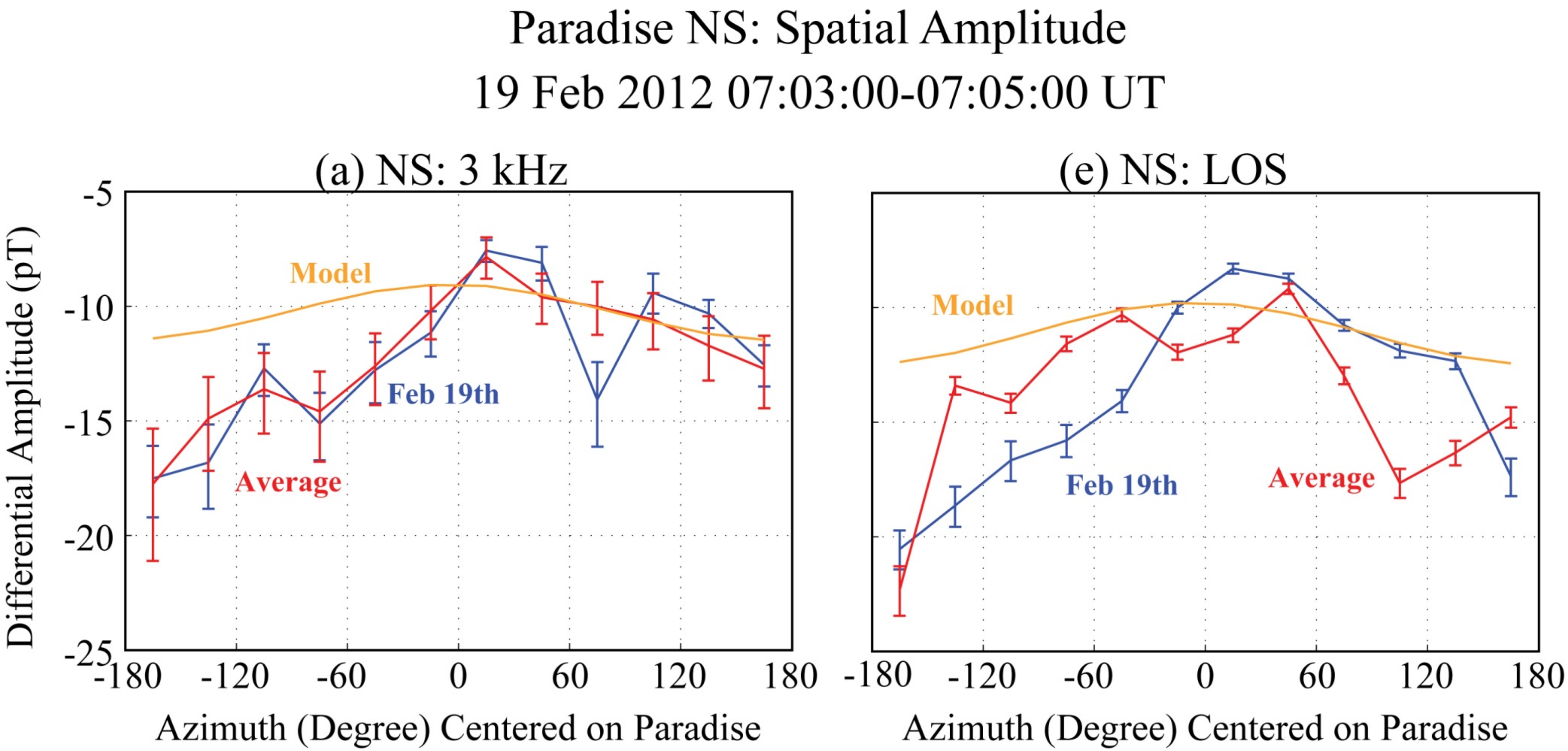
$\frac{\left|\sum_{i=1}^{N} A_i e^{j\phi_i}\right|}{\sum_{i=1}^{N} A_i}$ - Phasing Effect

D_{GM} - Duty Cycle Effect

$\frac{S_{GM}}{S_o}$ - Area Gain



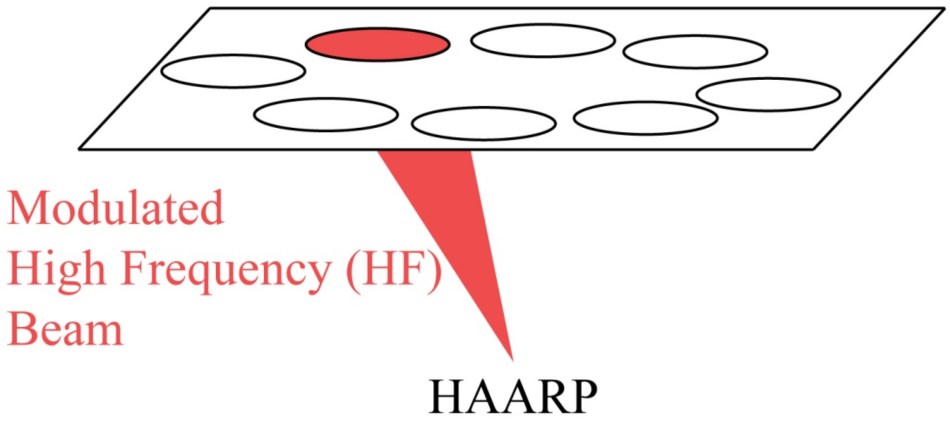
GM Observed at Paradise Spatial Amplitude



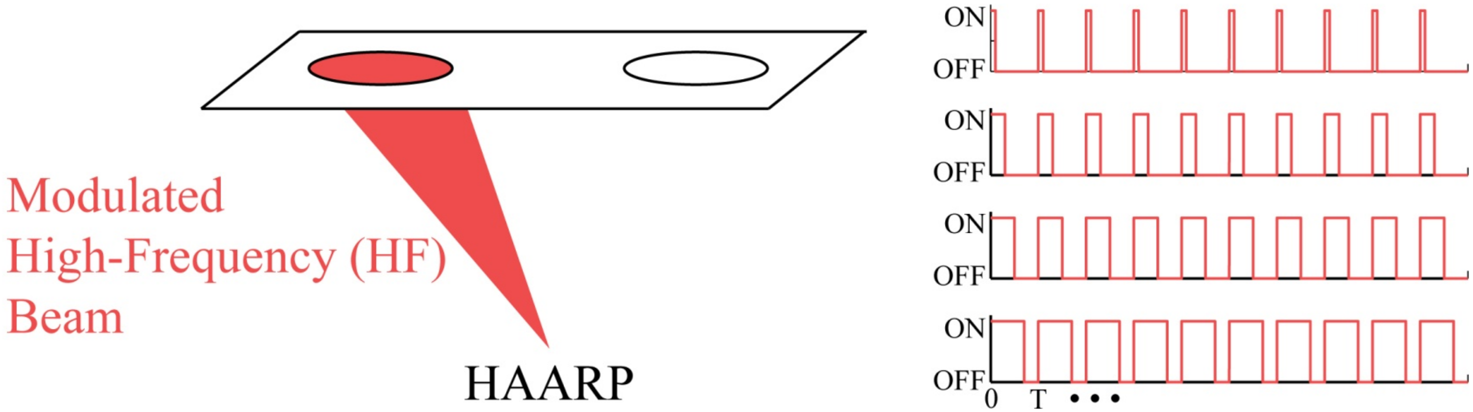
Optimizing the ELF/VLF Source

Experiment: Optimal Heating

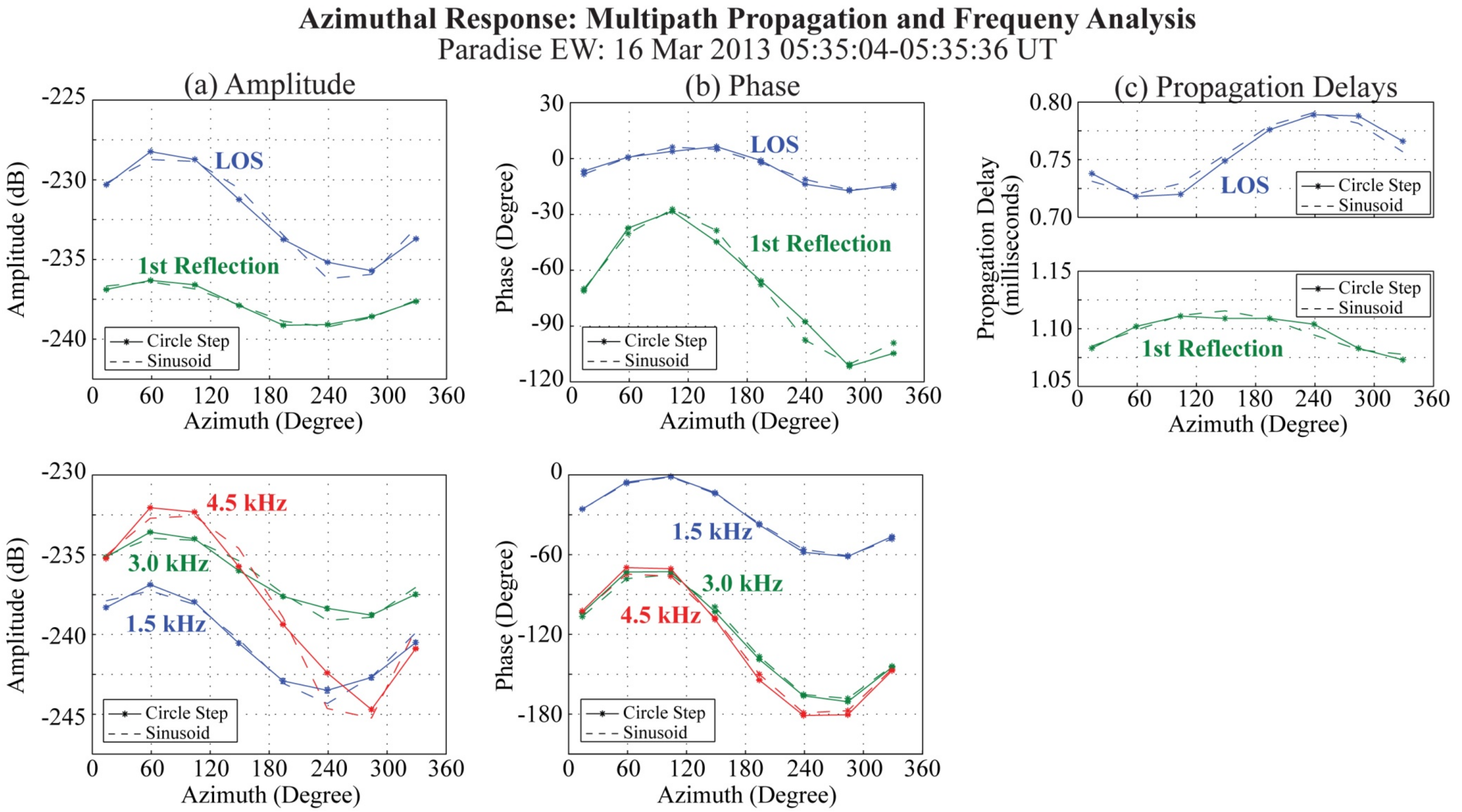
Experiment 1: Circle Step



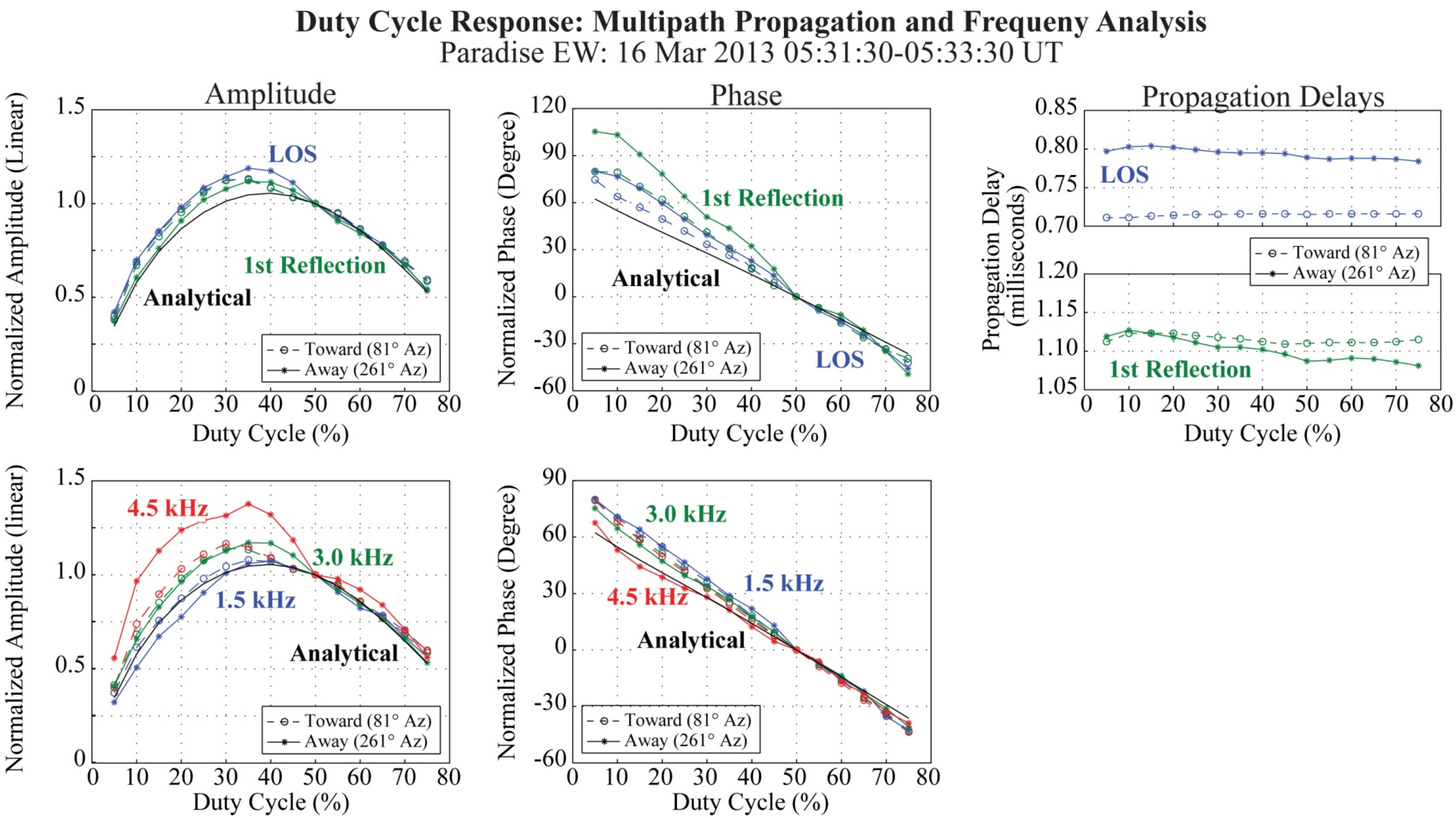
Experiment 2: Duty Cycle Step



Azimuthal Step

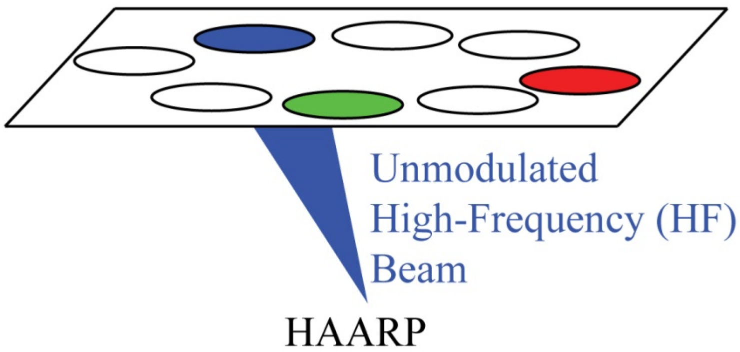


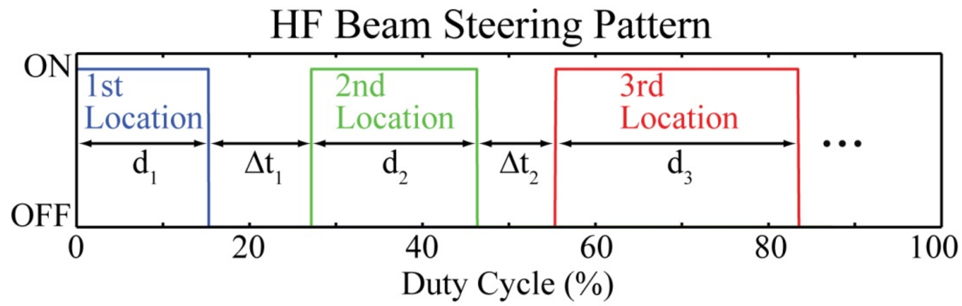
Duty Cycle Step



τ_h=28.2 micro sec, τ_c=100 micro sec

Heating Pattern Diagram





The total received amplitude is,

Frequency: $S = |\sum A_k e^{j\varphi_k} D_k(d_k) e^{-j2\pi\sum(d_{m-1}+\Delta t_{m-1})}|$

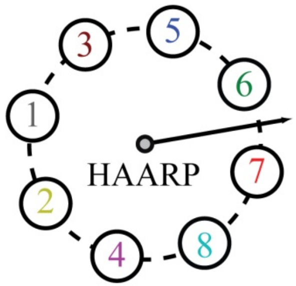
Propagation path: $S = \max|\sum A_k e^{j\varphi_k} D_k(d_k) \mathit{sinc}\{B(t-\tau_k)\} e^{j2\pi fc(t-\tau)} e^{-j2\pi\sum(d_{m-1}+\Delta t_{m-1})}|$

N: Total number of heating locations
A_k: Amplitude at k^{th} heating location
φ_k: Phase at k^{th} heating location
D_k: Duty cycle spectrum at k^{th} location

d_k: Beam-on time at k^{th} heating location
Δt_k:Beam-off time between k^{th} and $(k+1)^{th}$ location
B: Bandwidth of the frequency ramp
fc: Center frequency of the frequency ramp

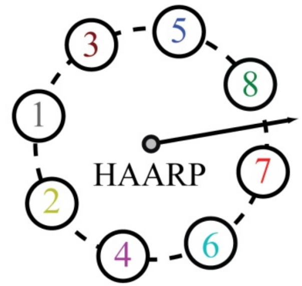
Optimized Timing at Three Frequencies

1562.5 Hz



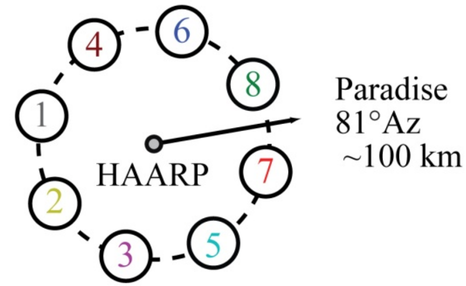
1: 60 μsec
2: 35 μsec
3: 35 μsec
4: 25 μsec
5: 60 μsec
6: 60 μsec
7: 60 μsec
8: 40 μsec
OFF: 265 μsec
Total: 640 μsec

3125.0 Hz



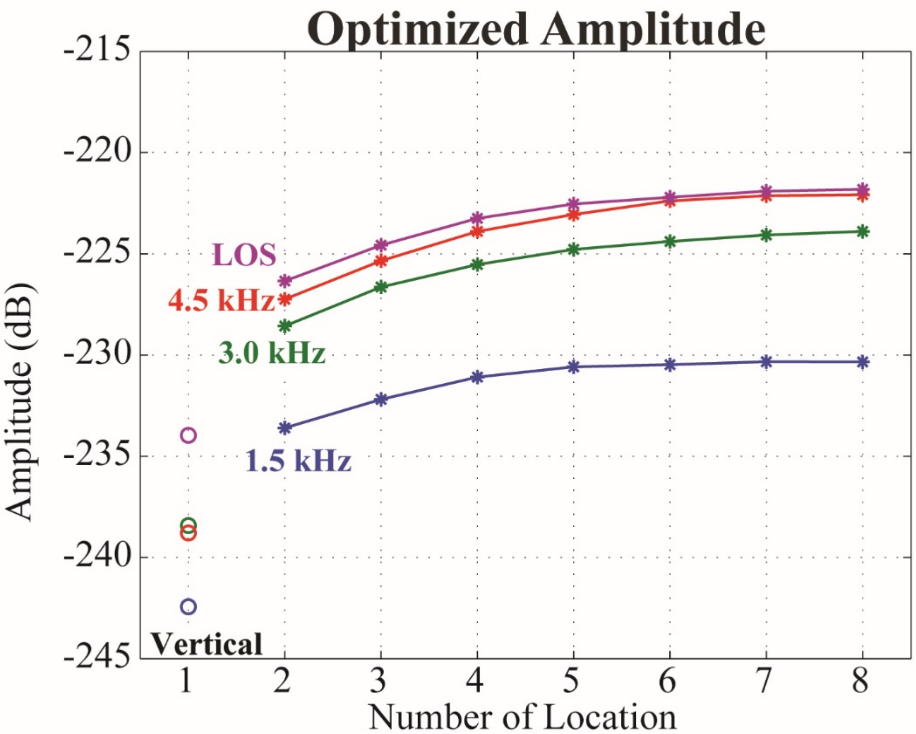
1: 40 μsec
2: 30 μsec
3: 20 μsec
4: 15 μsec
5: 30 μsec
6: 15 μsec
7: 30 μsec
8: 50 μsec
OFF: 90 μsec
Total: 320 μsec

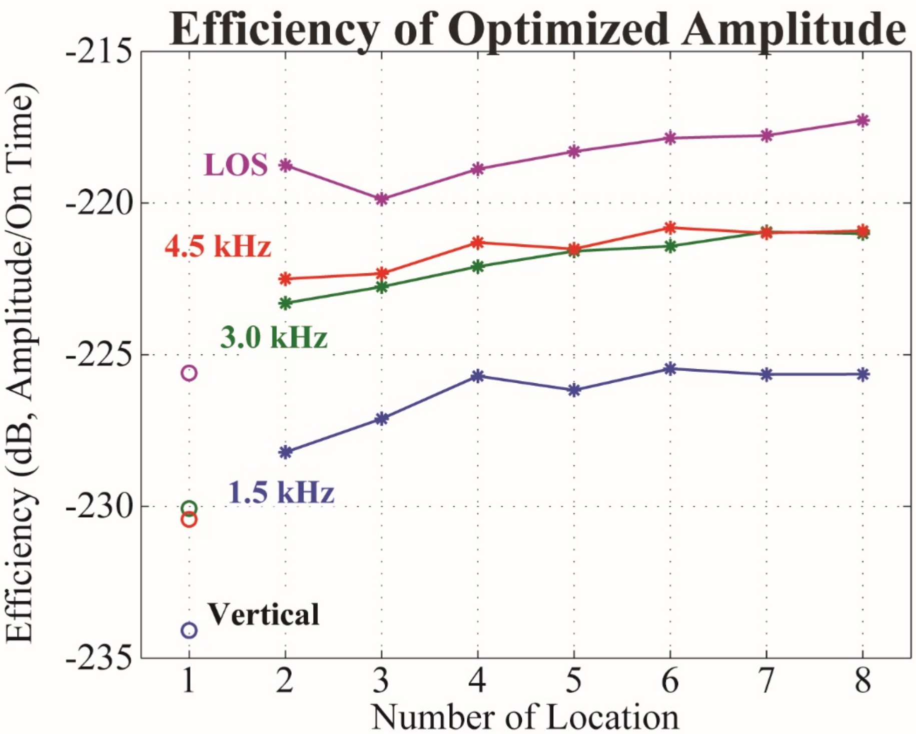
5000.0 Hz



1: 15 μsec
2: 20 μsec
3: 20 μsec
4: 10 μsec
5: 20 μsec
6: 20 μsec
7: 20 μsec
8: 20 μsec
OFF: 55 μsec
Total: 200 μsec

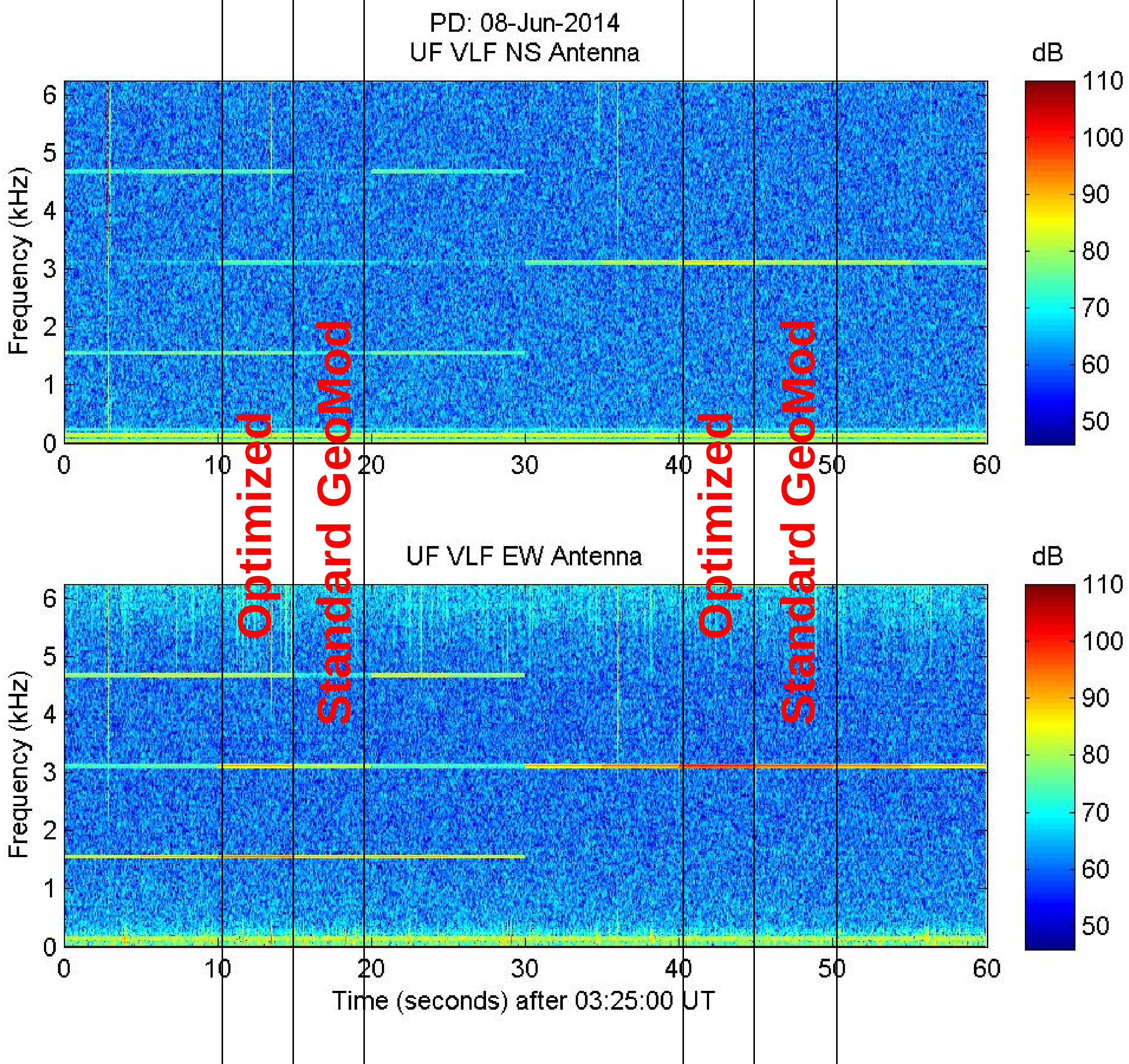
Predicted Optimized Amplitude



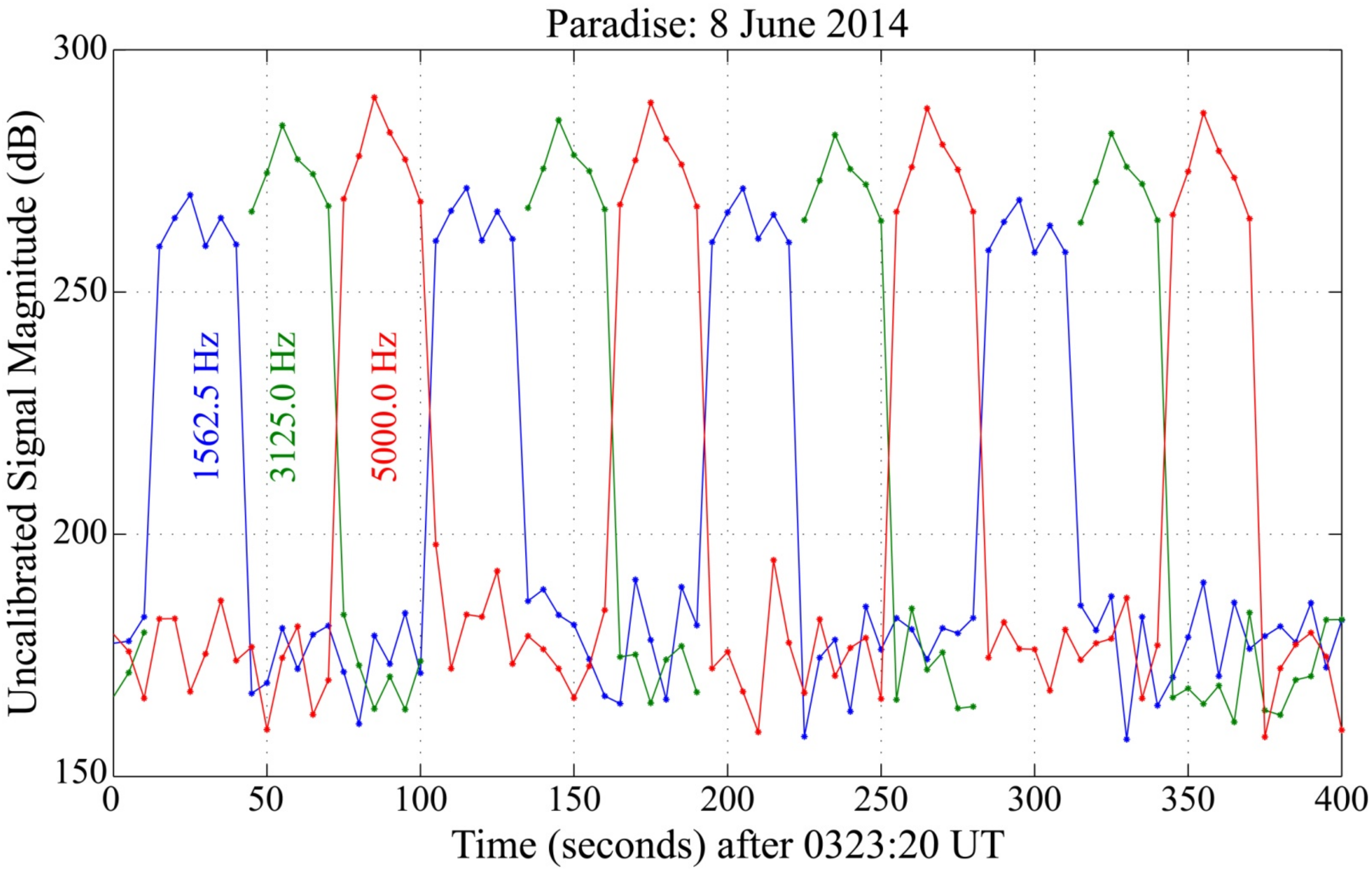


Compared to geometric modulation,
amplitude is increased by **~7 dB** and efficiency is increased by **~11 dB**

Experimental Observations


PD: 08-Jun-2014
UF VLF NS Antenna
UF VLF EW Antenna
Frequency (kHz)
Time (seconds) after 03:25:00 UT
dB
Optimized
Standard GeoMod
Optimized
Standard GeoMod

Experimental Measurement: Magnitude Comparison



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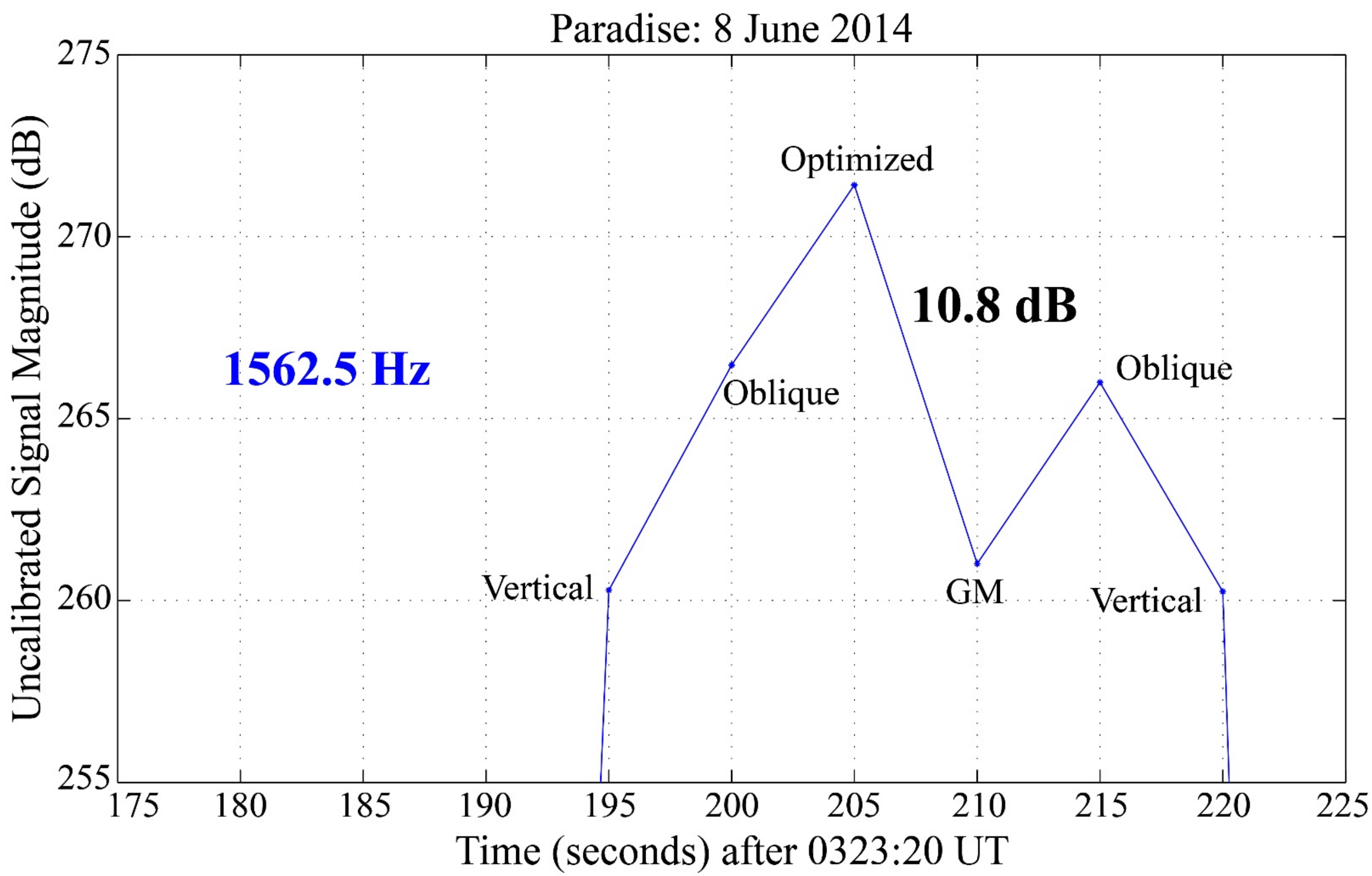

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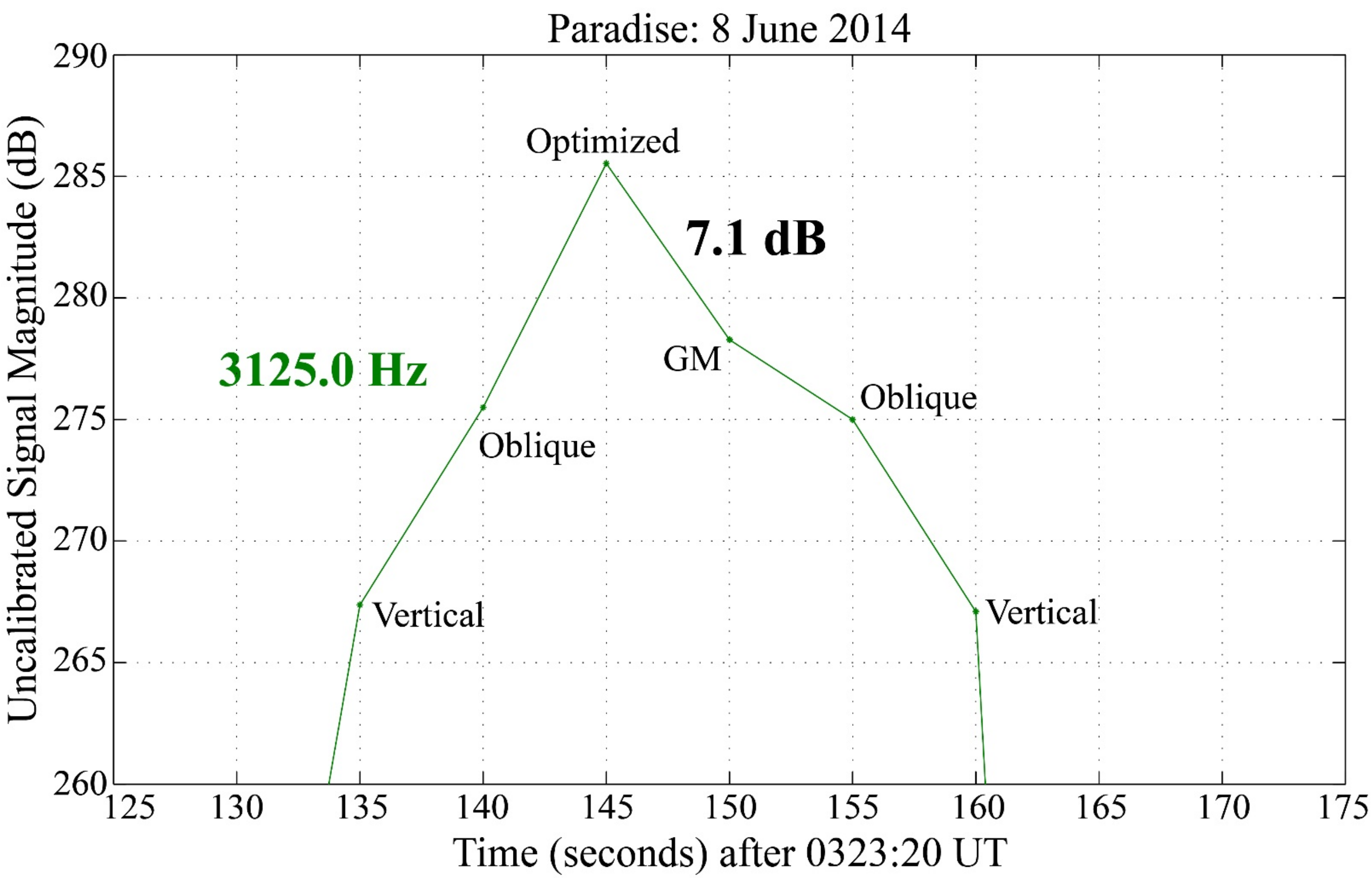

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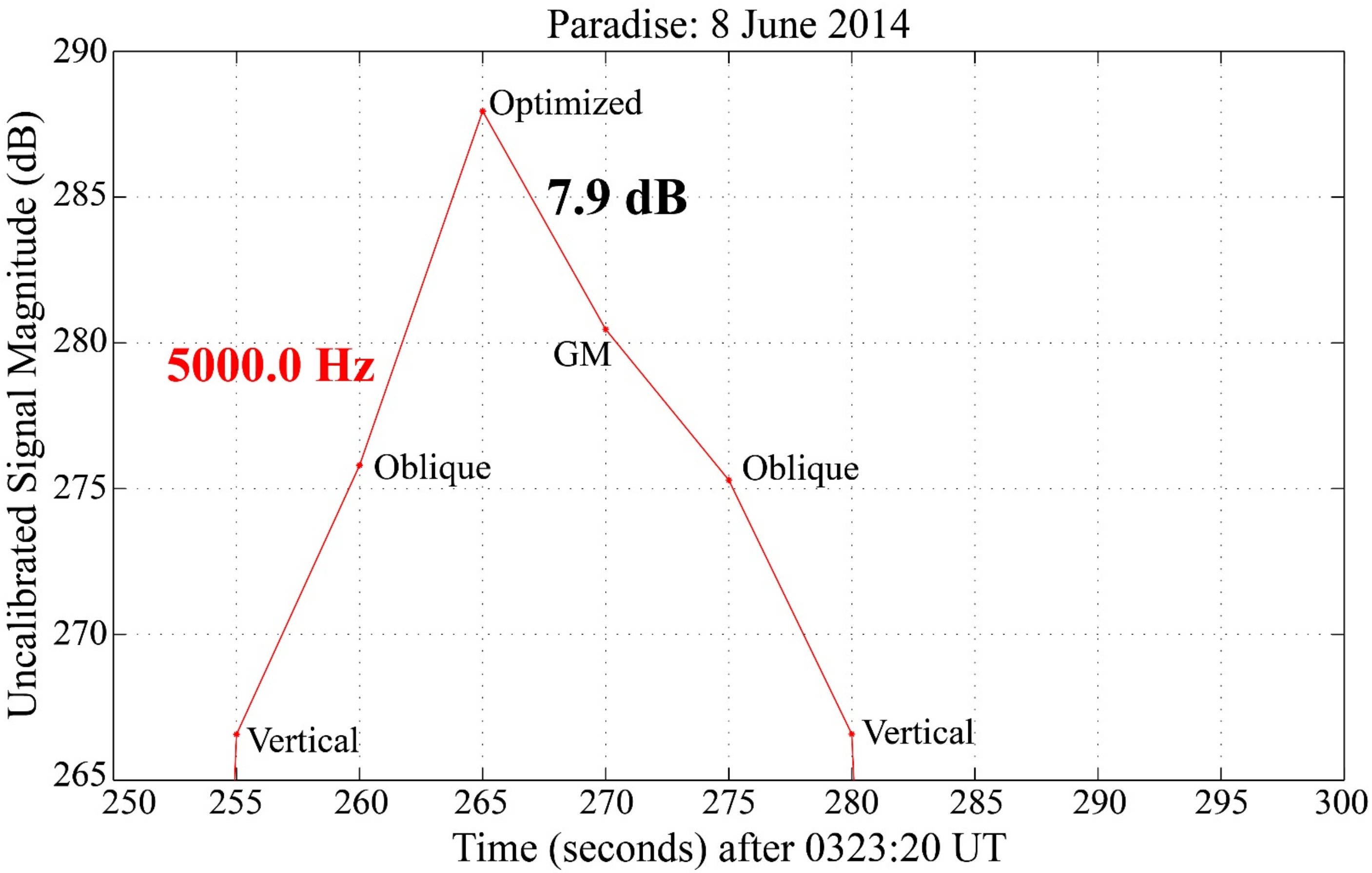

Magnitude Comparison

- 1562.5 Hz
  - Optimized Magnitude 10.8 dB larger than for GM
  - Optimized Efficiency 13.1 dB larger than for GM
- 3125 Hz
  - Optimized Magnitude 7.1 dB larger than for GM
  - Optimized Efficiency 8.5 dB larger than for GM
- 5000 Hz
  - Optimized Magnitude 7.9 dB larger than for GM
  - Optimized Efficiency 9.3 dB larger than for GM

Summary

- TOA analysis is employed to successfully discount EI waveguide propagation effects
- Dual-beam heating: Broad agreement between theory and model (first harmonic analysis)
- Beam Painting/Geometric Modulation: Optimization is possible, but must rely on experimental observations
- Magnitude gains of 7-11 dB are demonstrated
- Efficiency gains of 8-13 dB are demonstrated