C4: Collaborative Work on Novel Approaches to ELF/VLF Generation

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C4: Collaborative Effort

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C4: Goals and Actions

Going Beyond Simple AM ELF Generation

➢ Improve Efficiency
  • Investigate Radiated ELF Signal versus HF ERP
  • Improve Efficiency with Beam Scanning Techniques
  • Improve Efficiency /Directionality using Dual Beam- Special Shape Schemes
  • Take Advantage of Communication Channel

➢ Improve Reliability
  • Understand Dependency on Electrojet and Ionospheric Conditions
  • Quantify Potential Improvements from Modulating Equatorial Electrojet

➢ Perform collaborative ELF campaigns that bring together the resources from several centers to move forward in resolving efficiency, reliability, channel utilization. – OCT 2010, MAR 2011
C4 Experiments

1) Long Distance Illumination
2) “Beam Stacking”
3) “Beam Painting” for $f < 500\text{ Hz}$
4) HF Beam Shape/Pattern
5) Time of Arrival Analysis of Geometric Modulation
6) Power Dependence
7) Twisted Beam
8) Controlling ELF/VLF Harmonic Content
General ELF/VLF Receiver Overview
Stanford Receiver Network

HAARP

• Poker Flat
• Healy
• Dot Lake
• Chistochina
• Valdez
• Homer
• Yakutat
• Juneau
• Kodiak
• Ketchikan
Stanford Receiver – Pictures
Improved Stanford Front End

Noise Response (assumes 10m base triangle antenna)

Frequency (kHz)

Noise Level dB-pT/sqrt(Hz)
UF Receiver Locations

Separate systems for
- ELF/VLF (500 Hz- 40 kHz)
- low-ELF (<500 Hz)
Sportsmen’s Paradise

50 kHz

Lightning-generated Sferics
Navy VLF Transmitters
HAARP-Generated ELF
Russian Alphas

0 Hz

60 seconds
UC Denver/Stanford Receiver

- Richardson highway between Glenallen and Paxson
- Orthogonal in azimuth to Chistochina-HAARP line

Paxson UCD Site

- Chistochina (Stanford)
- Paradise (UF)
- HAARP
- Valdez (Stanford)
Paxson Spectrograms

Paxson; Channel 0 (Joint Stanford and UC Denver ELF/VLF)

Frequency [kHz] (Δf = 12.21 Hz)

Seconds after 2010-10-12 06:00:00 [UT]

dB-pT
Paxson Spectrograms

Paxson; Channel 0 (Joint Stanford and UC Denver ELF/VLF)

North-South Paxson AWESOME Data, 12–Oct-2010

University of Colorado
Denver

UF
University of Florida

NAVSEA
Experiment: Long Distance Propagation

History

- Detection at 4400 km (Midway Island), 960 kW HAARP ~2 kHz signal, 30 minute integration [Moore et al., 2007]

- Detection at 4400 km (Midway Island), 3.6 MW HAARP ~2 kHz, ms integration [Cohen et al., 2010]
NUWC ELF Receiver at Fisher’s Island – No HAARP observations to date

FSK Modulation Format (~400 Hz) observed at closer sites in Alaska
ELF Signals at Juneau (~700 km)

Juneau 11-Oct-2010  N/S Antenna

E/W Antenna, Bins Normalized by ΔF = 0.017Hz

1 minute integration time
ELF Signals at Santa Cruz (3200 km)

1 minute integration time
Uses of Beam Steering

- AM heating an oblique angle
- Tromso facility
- Some directionality toward beam tilt
- Barr et al. [1984]

- Alternating HF beam between two locations
- Tromso facility
- System acted as 2 independent antennas
- Barr et al. [1987]

- Rapid beam movement during ON portion
- Requires high ERP and rapid beam steering
- Papadopoulos et al. [1989]

- Unmodulated beam is steered in geometric modulation
- Generalized extension of two-location technique
- Cohen et al. [2008,GRL]
Experiment HF Beam Pattern

- Understand the effect of HF beam shape,
- Explore beam shapes that cannot be formed at HAARP directly
Adding 3 Narrow Beams

TOA Analysis: Paradise Magnitude 07 October 2010, 0645 UT

- TOA: Time of Arrival Analysis
- Determine arrival time from broadband 1-5 kHz ELF frequency-time ramps
Frankenstein vs. Broad

Paradise Magnitude 07 October 2010, 0655 UT

Amplitude (dB)

Time Delay (seconds) x 10^3

Direct Path Ionospheric Reflection

Broad 1
Broad 2
Broad 3
Normal Sum
Time of Arrival Analysis for Geometric Modulation

**Circle Sweep**

![Circle Sweep Diagram]

**Saw-Tooth Sweep**

![Saw-Tooth Sweep Diagram]
Circle vs. Narrow

The magnitude of Circle sweep is almost always larger (by 3dB) than the vertical narrow beam.
Circle vs. Narrow

- Width of main lobe does is same when both signals are normalized.
- Dominant source region is about the same size in both cases.
The sweep toward Juneau (observed at Paradise) is larger in amplitude in the main lobe, but smaller in amplitude in the ionospheric reflection.
Sweep to Juneau

The ionospheric reflection makes up a much larger component of the received signal generated by the narrow beam pattern.
AM vertical narrow beam is significantly stronger than the sweep toward Kodiak (observed at Paradise).
Sweep to Kodiak

TOA Analysis: Paradise Norm. Mag. 06 October 2010, 0852 UT

Amplitude (dB)

Time Delay (seconds)

Kodiak Sweep
AM Vertical
AM Vertical Noise
Sweep to Paradise

TOA Analysis: Paradise Magnitude 06 October 2010, 0838 UT

- Paradise Sweep
- AM Vertical
- AM Vertical Noise

Direct Path
Ionospheric Reflection
Sweep to Paradise

TOA Analysis: Paradise Norm. Mag. 06 October 2010, 0838 UT

- Paradise Sweep
- AM Vertical
- AM Vertical Noise
Experiment: Twisted Beam

- Allows comparison between circle sweep and AM beam that covers roughly the same area.
- Both have beam tilting effect, but only circle sweep has `phased array’ effect.
- Circle Sweep was also tilted, and run at both full/half power levels.
Twisted Beam and Circle Sweep

Twisted Beam

20-point Circle Sweep

Degrees N–S

0

50

Degrees E–W

0

50

Degrees E–W

0

50

0

-10 dB–rel

-20

-30

University of Colorado
Denver

University of Florida

NAVSEA
Twisted Beam vs. Circle Sweep Results

- Circle Sweep amplitudes increase with frequency
- Twisted Beam decrease with frequency
3D Model of HF-ELF conversion

- Electron temperature ($T_e$) determined from energy balance equation at each altitude
- HF power absorbed, ionosphere modified at each layer
- Tomko [1981], Moore [2007], Payne et al. [2007]

Electron energy balance equation

$$\frac{3}{2} N_e \kappa_B \frac{dT_e}{dt} = 2k\chi S - L_e (T_e - T_0)$$

- $N_e =$ Electron density
- $\kappa_B =$ Boltzmann’s constant
- $k =$ Wave number
- $\chi =$ Im($n$)
- $S =$ HF power density
- $L_e =$ Sum of loss terms

- Analytical full-wave solution of Earth-ionosphere waveguide propagation
- Assumed horizontally homogeneous ionosphere
- Described in Lehtinen and Inan [2008, GRL]

- Electrojet fields assumed geomagnetic north
- $\Delta \sigma_{\text{hall}}$ and $\Delta \sigma_{\text{hal}}$ generate currents from $J = \sigma E$

Figure from Piddyachiy et al. [2008, JGR]
Circle Sweep Theoretical Results
Circle Sweep has a null at center

- Null becomes smaller with higher modulation frequency

- At higher ELF frequencies circle sweep gives higher signal at observation point as observed
Follow-Up Experiment Idea....

- Repeat Circle Sweep and Twisted Beam with different zenith/azimuths
- Try to move that ‘null’ spot
- Must be done in 1-3 kHz range
Experiment: Beam Stacking

- Create vertical endfire array by splitting the beam and achieving altitude separation of effective modulation dipole

- Achieve Dipole Separation
  - Higher HF frequency → higher modulation altitude
  - Higher ERP → able to penetrate higher altitudes
  - O-mode vs. X-mode
Beam Stacking Earlier Result

The experiment presented here involved splitting the HF array 60%-40% and modulating the larger half with the 2nd harmonic of the smaller half.
Experiment Formats Oct 2010/Mar 2011

Co-located Beams

Separate Beams
Direct vs. Indirect Beamstacking

**Direct Beamstacking:**
Beam1: HF1, \( f_{\text{ELF1}} \)
Beam2: HF2, \( f_{\text{ELF1}} \)

**Indirect Beamstacking:**
Beam1: HF1, \( \frac{1}{2} f_{\text{ELF2}} \)
Beam2: HF2, \( f_{\text{ELF2}} \)

Second harmonic of one beam interacts with first harmonic of second beam

Second harmonic originates either directly from signal or from non-linearities in the ionosphere
8 Separated Beam Formats

North Array
(2.75 MHz, X mode, Vertical, Nrows, 50% square wave)

Control Tones (4 seconds)
1 sec 1040 Hz
1 sec OFF
1 sec 4060 Hz
1 sec OFF

Phased Tones (54 seconds)
for phi=0:30:330
1.5 sec 1040 Hz
1 sec 1040 Hz
1 sec 2080 Hz
1 sec 3020 Hz

2 seconds OFF

South Array
(HF2, MODE2, Vertical, Srows, 50% square wave)

1 sec OFF
1 sec 1040 Hz
1 sec OFF
1 sec 4060 Hz

1.5 sec 1040 Hz +phi
1 sec 2080 Hz +phi
1 sec 3020 Hz +phi

Phase cycles from 0-360 degrees

TABLE OF VERSIONS

<table>
<thead>
<tr>
<th>Version</th>
<th>HF2</th>
<th>MODE2</th>
<th>Nrows/Srows</th>
<th>Name</th>
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<td>X</td>
<td>5/6</td>
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<td>5/6</td>
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</table>
16 Co-located Beam Formats

**North Array**
(2.75 MHz, X mode, Vertical, Nrows, Nmod)

**Control Tones (4 seconds)**
- 1 sec 1040 Hz
- 1 sec OFF
- 1 sec 4060 Hz
- 1 sec OFF

**Phased Tones (56 seconds)**
- for phi=0:15:165
- 1.5 sec 520 Hz
- 1 sec 1040 Hz
- 1 sec 2030 Hz
- 1 sec 3020 Hz

**South Array**
(HF2, MODE2, Vertical, Nrows, 50 % square wave)

- 1 sec OFF
- 1 sec 1040 Hz
- 1 sec OFF
- 1 sec 4060 Hz

**Phase cycles from 0-180 degrees**

**TABLE OF VERSIONS**

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<td>9.4 MHz</td>
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<td>sinusoidal</td>
<td>3/8</td>
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</tbody>
</table>
Both Sites SEP 1

HF1: 2.75 MHz 5 rows X
HF2: 5.8 MHz 6 rows X

Chistochina

Paxson

3020 Hz direct
2080 Hz indirect
Both Sites SEP 3

HF1: 2.75 MHz 5 rows X
HF2: 5.8 MHz 6 rows O

Chistochina
3020 Hz direct

Paxson
2080 Hz indirect
Co-located Beams I

HF1: 2.75 MHz 5 rows X, sine
HF2: 5.8 MHz 6 rows X, square
Nulls at 90 degrees (180 degrees for the second harmonic)
Co-located Beams II

HF1: 2.75 MHz 3 rows X, square
HF2: 5.8 MHz 8 rows O, square

ELF Phase Difference between Beams

dB (rel)
Vertical Directionality of HF Heating
Radiation Pattern with Phase Shift

Magnetic field from beam stacking 2 kHz

North–South distance (km)

East–West distance (km)

dB compared to magnetic field in phase

36 degrees 72 degrees 108 degrees

144 degrees 180 degrees 216 degrees

252 degrees 288 degrees 324 degrees
Radiation Pattern with Phase Shift

- Weakest fields on ground occur for 216 degrees.
Variety of Ionospheric Models

Models show that beamstacking results are strongly influenced by ionospheric profile.

- Simulations run with 10 ionospheres
- E and F regions specified from IRI
- D region specified from Wait and Spies two-parameter
- One day and 9 nighttime flavors
Theoretical calculations

- Null of interference pattern occurs at moves as a function of phase for different ionospheres.
- Technique could serve as potential D-region diagnostic tool.

Theoretical Signals at Chistochina

- $h=95$ km
- $h=90$ km
- $h=85$ km
- $h=70$ km

$b=0.75$  $b=0.62$  $b=0.50$  $b=0.45$
Theoretical calculations
Theoretical calculations

Theoretical Signals at Chistochina

- 2.75M X, 1k sq50
- 5.80M X, 2k sine
- Double (1 kHz)
- Double (2 kHz)

b=0.75  b=0.62  b=0.50  b=0.45
Summary

- C4 Collaborative effort has effectively brought together the resources of four centers to pursue novel generation techniques and better understand efficiency and reliability of ELF generation.

- Long distance transmissions being pursued with formats relevant for naval communications.

- Multiple experiments have been performed to investigate effect of beam shape and beam sweeping (geometric modulation).

- Beam-beam interactions (beamstacking) can favorable inject waves into waveguide and also provide D-region diagnostics.