HAARP IRI Operations
Capabilities and Limitations

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Presentation Overview

- **Ionospheric Research Instrument (IRI) Phased Array**
  - Static performance
  - Beam shape, beam pointing
  - Active impedance (scan impedance)
  - Frequency dependent effective radiated power (ERP)

- **IRI Control System**
  - Control system features
  - Modulation capabilities
  - A few examples
HAARP IRI 12x15 Planar Phased Array
oriented 14° E of N

Magnetic North: 20.3° in 2012
-0.3° per year

True North
HAARP IRI Array - Capabilities

• **360 dipoles with independent phase and amplitude control**
  • Amplitude/Power controlled by fast automatic level control (ALC) circuit in each transmitter
    • 10 kW maximum output per dipole
    • Programmed amplitude control voltage can be static or dynamic
      • amplitude modulation (AM), power stepping, etc.
    • Extremely linear amplitude variation vs. control voltage down to 10 watts per transmitter
  • Phase controlled by fast phase-lock-loop (PLL)
    • RF source is distributed throughout array using equal-length coax cables
    • Feedback signal taken from transmitter output forward sample (directional coupler)
    • Phase can be static or dynamic with ~10 usec minimum change time
    • PLL can run open-loop with pre-corrections for rapid beam scanning

• 360 Dipole currents are monitored (digitized) in real-time
  • Amplitude and phase (I&Q) recorded at 200 kHz rate
  • Snapshots of captured data used to calculate radiation pattern based on real dipole currents
HAARP IRI Array - Limitations

- Dipoles are large structures, closely spaced, and therefore coupled electromagnetically
  - Active ALC and PLL maintains correct forward power and phase despite tight coupling
  - However, coupling strongly affects the **impedance** seen by each transmitter
  - Transmitters must be tuned to something close to this “active impedance”
  - Severely mismatched transmitters may not be able to operate (or may operate at reduce output)

- Cannot switch between very different phase conditions without retuning
  - Beam pointing angle change > 15 deg requires retuning
  - Broadened beam requires retuning vs. normal beam
  - Most “novel” beam modes require retuning vs. normal beam
  - Retuning requires up to 30 seconds OFF

- Power can only be reduced from 10 kW per dipole
  - Gaussian beam modes (tapered excitation) always result in lower ERP
Dipole Impedance (as seen by TX)

Forward/Reflected Power

4.50 MHz

10 dB
Impedance vs. Scan Angle

4.5 MHz
zenith=0°, azimuth=0°
Impedance vs. Scan Angle

4.5 MHz
zenith=15°, azimuth=0°
Impedance vs. Scan Angle

4.5 MHz
zenith=30°, azimuth=0°
### Impedance vs. Scan Angle

4.5 MHz
zenith=45°, azimuth=0°

| 1025° | 932° | 839° | 745° | 652° | 559° | 466° | 373° | 280° | 186° | 93° | 0° |
|-------|------|------|------|------|------|------|------|------|------|-----|----|---|
Impedance vs. Scan Angle

4.5 MHz
zenith=60°, azimuth=0°
HAARP IRI Array - Dipole Coupling

- IRI Array is designed to operate best with a normal beam within 15 deg of broadside
  - Antenna matching circuits were optimized for this condition, given the known coupling
  - Low-frequency performance (e.g., < 4 MHz) actually requires coupling
    - Isolated dipoles have nearly full reflection without neighbors

- Dipole coupling affects our ability to operate with arbitrary phasing
  - Impedance may improve or worsen depending on neighboring phases and operating frequency
  - Significant impedance mismatch (vs. 50 ohms) means high reflection, low radiated power
  - If impedance mismatched is too high, transmitter may not be able to operate at all
2.7 MHz Magnetic Zenith
4.8 MHz Magnetic Zenith
6.8 MHz Magnetic Zenith

N/S pattern
- width: 7.9 deg
- peak sidelobe: -12.9 dB

E/W pattern
- width: 6.1 deg
- peak sidelobe: -13.2 dB

Array Gain: 28.3 dBi
ERP: 93.5 dBW
Polarization: RCP
Isolation: 30.0 dB
7.8 MHz Magnetic Zenith
9.2 MHz Magnetic Zenith
IRI Array: Total Reflected Power
for 3600 kW Forward Power (broadside)

10% reflected
VSWR 1.9:1

frequency (MHz)
HAARP IRI Array Effective Radiated Power
HAARP Control System - RF Capabilities

- **Two Independent RF Signal Generators**
  - Two RF distribution channels -- equal length coax to each transmitter
  - Each transmitter can select RF1 or RF2 source via control bits (rapid switching)
    - Split array / subgrids can use one or two RF sources (dual frequency)
  - Frequency ramps/steps can be accomplished with:
    - FM waveform (analog waveform applied directly to RF source)
      - arbitrary waveform shape, +/- 100 kHz maximum frequency deviation
      - 30 kHz maximum waveform frequency
    - Single RF source stepping
      - 100 msec OFF required between steps
      - uniform or arbitrary steps, 200 kHz bandwidth (or more at higher HF)
    - Dual RF source toggling (minimum 100 msec dwell at each step)
      - allows fast steps with no off time
      - requires both RF sources, so no split array
HAARP Control System - Modulation Capabilities

- **Two Independent Modulation Sources**
  - Direct digital synthesis at 200 kHz
  - Digital waveform data injected directly into real-time control data stream
  - D/A conversion takes place at transmitter input

- **Modulation states locked to power/phase control states**
  - Allows synchronized power control and beam pointing with modulation change
  - Starting phase always well defined with respect to experiment start (i.e. GPS time)

- **Arbitrarily complex sequences of modulation states can be created**

- **Timing and frequency accuracy provided by 10 MHz rubidium frequency standard**
  - Locked to GPS for long-term stability
  - Distributed throughout site for locked receiver applications
HAARP Control System - Modulation Capabilities (AM and FM)

- **Waveforms**
  - Sine, half-sine, rectified sine (sqrt sine), square, sawtooth
  - Any waveform that can be defined as a function of phase angle can be added
  - Any waveform can be used with any frequency type (e.g. fixed or ramp)

- **Modulation frequencies**
  - Fixed, linear ramp, log ramp, parabolic ramp
  - 0-30 kHz range
  - All modulation frequencies are precise -- locked to common 10 MHz reference

- **WAV file**
  - For very complex waveforms, user can provide a WAV format file
  - Any sample rate -- internally resampled to 200 kHz
  - -32767/+32767 (16 bit signed) data range translates to 0-100% output (amplitude modulation)
HAARP Control System - Modulation Capabilities (Pulse)

- Direct Digital Synthesis at 1 MHz sample rate
- Single Pulse (width, delay)
  - 80 dB on/off ratio
  - Minimum pulse width: 10 µsec
  - Width/delay resolution: 1 µsec
  - PRF: 0-30 kHz
- Pulse Train (arbitrary list of widths and delays)
- Coded Pulse
  - Barker (2-13 chips) or user supplied (e.g. “11100010010”)
  - Coded via bi-phase (0/180 RF phase switching)
  - 10 µsec minimum chip length
- Pulse shaping applied at transmitter low-level drive
  - Selectable risetime (1 - 10,000 µsec)
  - Selectable shape: 1% truncated gaussian or raised cosine
  - 100 MHz D/A shaping via look-up table
Example: Complicated frequency-time modulation experiment

This was an ELF experiment conducted during the Optics 2008 campaign, designed to scatter bursts of electrons out of the loss cone, producing optical emission.

Freq-time curves were the result of a modeling program (provided by PI).

Accomplished with a script that converts freq-time data to multiple linear freq ramp segments, with generated waveforms stored in WAV files.
Spectrogram of transmitted waveform:
Another example (not so scientifically useful but...)

Gen. BEDKE
Dual-Frequency Transmission: North/South Split Array

For closely-spaced frequencies, the offset in sub-array phase centers produces an interference pattern in the radiation…
Beam Scanning: North/South Sawtooth Sweep

... very similar to a beam scanning mode
Synthesized Two-Frequency Mode

Sqrt-sine modulation waveform synchronized with 180 deg RF phase change produces pure two-frequency transmission.
In Summary…

• **HAARP offers a great advantage to active ionospheric modification experiments**
  • High radiated power (3.6 MW transmitted, up to 4 GW ERP)
  • Tremendous flexibility in
    • transmit frequency
    • beam control
    • split array
    • complex modulation types
    • software-based control system