The Physics of Ionospheric Modifications
Issues that Impact the Source Design

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MURI Review
June 12, 2015

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Ionospheric Modifications Using HF Heaters

Space as an open plasma laboratory

Measure in “cause & effect” mode the effects on the ionosphere & magnetosphere plasma due to controlled and targeted HF heating. Triggered response spans from cm to Mm

Tests conducted using large, fixed facilities e.g. HAARP (3.6 MW, 95 dBW ERP); physics and apps depend on geomagnetic latitude (θ, B)

- **Virtual Antennae at ELF/VLF**
- **Artificial Plasma Layers (APL)**
- **Artificial Ionosph. Turbulence (AIT)**
- **Bi-static links at UHF and L-band**
- **Plasma outflows & ducts**

<table>
<thead>
<tr>
<th>Heater</th>
<th>θ</th>
<th>L</th>
<th>f MHz</th>
<th>P_R MW</th>
<th>Gain dB</th>
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<tbody>
<tr>
<td>HAARP</td>
<td>14.5</td>
<td>4.9</td>
<td>2.7-10.</td>
<td>3.6</td>
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<tr>
<td>EISCAT</td>
<td>12</td>
<td>6.1</td>
<td>3.9-8.0</td>
<td>1.2</td>
<td>30</td>
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<td>SURA</td>
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<td>2.6</td>
<td>4.5-9.0</td>
<td>.75</td>
<td>26</td>
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<td>PLAT</td>
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<td>2.3</td>
<td>2.7-10.</td>
<td>1.4</td>
<td>19</td>
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<td>Arecibo</td>
<td>50</td>
<td>1.7</td>
<td>5 &amp; 8</td>
<td>80 &amp; 84</td>
<td>23 &amp; 26</td>
</tr>
</tbody>
</table>
Theory Objectives

• Explore IM Physics & MH requirements for regions that heating experiment were never conducted (e.g. dip equator) or conducted at low powers (mid-latitudes)
• Physics understanding and MH requirements for incomplete or controversial high latitude experiments (HAARP, EISCAT) – (See publication list)
• MH as a radar for Space Situation Awareness situations (e.g. CME detection)
• Design and, in collaboration with UCLA, conduct PoP experiments of the new physics concepts
• Use results of the investigations to provide required design requirements to source and antenna developers
## Preview of Design Specifications (Preliminary)

<table>
<thead>
<tr>
<th></th>
<th>Ion region</th>
<th>Latitude</th>
<th>Gain dBi</th>
<th>Rad Power MW</th>
<th>ERP dBW</th>
<th>f MHz</th>
<th>Polarization</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Virtual Antenna</strong></td>
<td>D/E</td>
<td>Dip Equator</td>
<td>5</td>
<td>1</td>
<td>65</td>
<td>4-8</td>
<td>Linear</td>
<td>10 kHz</td>
</tr>
<tr>
<td><strong>Ejet</strong></td>
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<tr>
<td><strong>Virtual Antenna</strong></td>
<td>F</td>
<td>Dip Equator</td>
<td>7-10</td>
<td>5-10</td>
<td>75-80</td>
<td>4-10</td>
<td>Linear</td>
<td>200 Hz *</td>
</tr>
<tr>
<td><strong>ICD</strong></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td><strong>CME Detection</strong></td>
<td>NA</td>
<td>Any appropriate</td>
<td>15-20</td>
<td>4 MW</td>
<td>80-85</td>
<td>20-100</td>
<td>O-X</td>
<td>TBD</td>
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<td></td>
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<td>Space Radar</td>
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<td><strong>Artificial</strong></td>
<td>F</td>
<td>Dip Equator</td>
<td>7-10</td>
<td>10 MW</td>
<td>80-85</td>
<td>4-10</td>
<td>Linear</td>
<td>NA</td>
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<td><strong>Turbulence</strong></td>
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</tr>
<tr>
<td><strong>Ducts</strong></td>
<td>F</td>
<td>Middle Latitude</td>
<td>7-10</td>
<td>10 MW</td>
<td>80</td>
<td>4-10</td>
<td>O</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Comments:**
1. Spitze angle constraints too demanding for high latitude applications (substorm, artificial ionization); 2. Langmuir Turbulence favored over UH; 3. Confidence ranking **Red, Green, Blue**
Ionospheric Modifications
Virtual Antennae

Pressure Gradient F-region → Diamagnetic Currents → Virtual Antennae at ELF/VLF → ELF/VLF injection to EIW & RB

Inject RF EM Waves → Electron Heating → Conductivity Modification E-region → Current Modification

F-Region - Collisionless
Electrojets Collisional Heating

ELF/VLF applications: Underwater Communications, Underground Imaging, Radiation Belts (w-p interactions, Remediation, Alfven Maser, Micropulsations, hiss, EMIC & chorus emissions,..)
Virtual Antenna @ ELF/VLF

Why?

Low efficiency of HED due to return current $M=I L \delta$. Lifting antenna to height $h$ reduces cancellation resulting in $M=I L h$ ($h \gg \delta$). If we drive an ac current in the ionosphere $M=I L H$

Two concepts: 1. Electrojet current modulation, D/E region

$E_{HED} / E_{VED} = k \delta \propto \delta / \lambda$

Bx, 02/10/2005, 06:52:59.7, $L = 4.36$, $\lambda = 60.59^\circ$, GMlon = 270.81$^\circ$, Alt. = 725.6 km

DEMETER
STANFORD

Gakona
BAE UMD

Ejectrojet (EJ)

Radiation Belt Injection

Conducting Ionosphere
Virtual Antenna @ ELF/VLF (cont.)

2. Ionospheric Current Drive (ICD) Concept (F-region)

Step 1: \[ \Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t) \]

Step 2: E field of MS wave drives Hall current in E-region resulting in secondary antenna resembling Ejet.
Mobile Heater Requirements for Virtual Antenna

Whether ICD or Electrojet, the moment of the virtual antenna scales linearly with the conductance $\Sigma$ of the D/E region, i.e.

$$M_{\text{eff}} \approx ILh, \quad I \approx \Sigma EL, \quad M_{\text{eff}} \propto \Sigma$$

$$M_{\text{eff}} \approx ILh \approx (\Sigma EL)Lh$$

$$M_{\text{eff}}(\lambda) \approx (5 \times 10^9)[\frac{\Sigma(\lambda)}{5S}](\frac{P_{HF}}{3.6MW})A - m^2 \approx$$

$$\approx (2.7 \times 10^8)\Sigma(\lambda)(\frac{P_{HF}}{MW})A - m^2$$

Notice the result is independent of the gain
Current Modulation Virtual Antenna Model

Density profile

Heating Code (HC)

Heater Parameters (ERP, f, duty cycle, modulation...)

C&B

E-field profile

conductivity

B field vs time
Equatorial Electrojet Modulation (D/E region)

MH Requirement

**MH Requirements:**
- Frequency Range 4-8 MHz
- Linear Polarization
- 5 dBi Gain
- 1 MW Radiated Power
- Modulation 1 Hz to 10 kHz
- No beam pointing

$$\begin{align*}
M &= (I / A)(L / km)(h / km) \Delta \, A - km^2 \\
I &= (J / A / km^2)(\Delta / km)(L / km) \, A \\
M &= JL^2 h\Delta \\
G &= 4\pi h^2 / L^2 \\
M &\approx J(4\pi h^3 / G)\Delta \, A$-km$^2$
\end{align*}$$

$M \approx 10^{10}$-$10^{11}$ A-m$^2$ at the dip equator region at FLF/VLF
Equatorial Electrojet Modulation
MH Requirement

Near Field for 100 kW linear polarization transmitter at 4 MHz sending .25 msec pulses. Ground B Field independent of Gain. Scales linearly with radiated power.
El Campo Texas Radar at 38.5 MHz
Operated in the late 60s by Gordon/MIT
Power 500 kW; 57.0 dBW
Gain 32.0 dB
Receive Antenna 18,000 m² (single polarization) 42.6 dBm²
Ionospheric Loss (37 MHz) −0.5 dB
Total Figure of Merit 131.1 dB
S/N 3dB (16 min, B=50kHz)

\[ \sigma \approx \pi R_s^2; R \approx 1 \text{ AU} \]
MH Requirements for Bi-static CME Monitoring

Potential receiving arrays: 1. Arecibo dish – 70000 m² (48.5 dBm²)
2. UTR-2 receiver in Ukraine – 140000 m² (51.5 dBm²)

Height \( h \) that TX & RX beams intersect determined by great circle angle and elevation angles.

Required frequency
20 MHz <\( f <100 \) MHz

Doppler Shift

FIGURE 5: The radially dependent plasma frequency of the solar corona at a temperature of \( 1.0 \times 10^6 \) K according to the models of Mann et al., Eq. (2), red curve; Baumgath-Allen, Eq (3), green curve; and Newkirk, Eq. (4), blue curve. The yellow strip covers \( 1R_\odot \).

Rodriguez, 1998; James, 1970
### MH Power and Gain Estimates

#### Multiple frequency & Multiple sites – Tomography Potential

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency Range</th>
<th>Transmit Power</th>
<th>Transmit Antenna Gain</th>
<th>Receive Antenna Area</th>
<th>Receive Antenna Gain</th>
<th>Ionospheric Loss</th>
<th>Total Figure of Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Campo Texas Radar</td>
<td>20-100 MHz</td>
<td>500 kW</td>
<td>57.0 dBW</td>
<td>18,000 m² (single polarization)</td>
<td>32.0 dB</td>
<td>−0.5 dB</td>
<td>131.1 dB</td>
</tr>
<tr>
<td>MH/Arecibo (20-100 MHz)</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>MH/UTR-2 (20-100 MHz)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>X-O polarization</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### MH Requirements:

- **Frequency Range**: 20-100 MHz
- **O-X polarization**: 15-20 dBi Gain
- **4 MW Radiated Power**: Possible low duty – High peak power possibility under study

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X-O polarization will allow measurement of the radial component of the magnetic field by using the differential delay of between O and X modes. Notice that Faraday rotation allows only the measurements of the fluctuations of Bn, while the mean field cancels out. Simultaneous multiple viewing angles and frequencies offer the potential of ground based tomography.
F-Region Equatorial/Middle Latitude Applications
ICD, AIT, Ducts, Acceleration, Optical Emissions, Ionization, ...

Spitze Angle Limitations
Equatorial F-region Heating – The Spitze Angle - ICD Requirements

Fig. 1: a) Ordinary mode waves and b) extraordinary mode waves at different angles of incidence. The Spitze angle is 17.95°.

Requires Gain. For vertical incidence only rays inside a 36 degree cone reach resonance. For equatorial F-region heating need 15 dBi gain. Alternatively we will waste more than half the power.

Fig. 2: Close-up of the rays O and X modes (cf. Fig. 1) near their turning points, and the locations of the plasma resonance (\(z_O = 238.99\) km) and upper hybrid (\(z_{UH} = 238.50\) km) layers. The Spitze angle is \(\chi_S = 17.95^\circ\).

- F-region Heating relies on Plasma or Upper Hybrid resonance. UH not available for MH at low geomagnetic latitude.
Equator, $f_{ce} = 0.85$ MHz

Arecibo

HAARP, $f_{ce} = 1.5$ MHz

Need for gain constraints utility of MH to lower latitudes
Anomalous Absorption – Heating- Acceleration in Langmuir Turbulence

8 MHz

No UH

Vertical field
The growth-rate of the PDI and OTSI instabilities at different heights for a vertically injected O mode with amplitude 1 V/m and .2 V/m at 150 km. There is a significant swelling of the O mode by about 7 at the first Airy maximum. The OTSI takes place for wavenumbers slightly higher than for the PDI. At the first few Airy maxima the OTSI dominates while at lower altitudes the PDI dominates. No significant instability takes place above the critical layer where $\omega=\omega_{pe}$ and the instability region is terminated about 5 km below the critical layer due to the onset of strong electron Landau damping.
Structure of Equatorial IAT lattice
Cigar vs. Pancake

\[ A = \text{SEMITHICKNESS OF HEATED REGION} \]
\[ W = \text{RADIUS OF HEATED REGION} \]
\[ L = \text{LONGITUDINAL (along field) IRREGULARITY SCALE SIZE} \]
\[ T = \text{TRANSVERSE IRREGULARITY SCALE SIZE} \]
\[ \left(\frac{\Delta N}{N}\right)_{\text{RMS}} = \text{RMS ELECTRON DENSITY FLUCTUATION} \]
\[ h_f = \text{HEATER REFLECTION ALTITUDE} \]

Fig. 8. The parameters of the scattering region.

Electric field amplitude

\[ 0 \leq \frac{E_z}{\text{V/m}} \leq 50 \]
\[ 225 \leq z \leq 240 \text{ km} \]

Ion density fluctuations

\[ 0 \leq n_i \leq 10^9 \text{ m}^{-3} \]
\[ 225 \leq z \leq 240 \text{ km} \]

Fig. 1: Schematic of SSS FAS system at GHz.

MUF at GHz, 10 cm

NEED FOR LAB EXPS- ONGOING – SEE UCLA PRES
Ionospheric Modifications
SEE- SLT-Acceleration
Artificial Aurora- Ionization

Bragg Reflectors
Density Irregularities AIT
HF/UHF/L-band scintillations
Diamagnetic Currents
Virtual Antennae at ELF/VLF
ELF/VLF injection to EIW & RB

Inject RF EM Waves
Electron Heating
Conductivity Modification
Current Modification

Ponderomotive Force
3 & 4 wave interactions
Low Frequency Waves (IA, LH)
ES to EM mode conversion
Stimulated EM Emission (SEE -No UH)

High Frequency Waves (epo, UH)
Strong Langmuir Turbulence
Electron Acceleration
Artificial Aurora Ionization
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<td><strong>Virtual Antenna Ejet</strong></td>
<td>D/E Dip Equator</td>
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<td>F Dip Equator</td>
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