Global Ionospheric Processes
AFOSR Space Science Program Review
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Overview of Current Task

• Four main focus areas:
  1. Ionospheric modification by chemical release
     • MOSC data analysis
  2. Ionospheric modification by HF heating
     • Unresolved scientific issues related to artificial layers
  3. Long-range equatorial HF radar
     • Scintillation monitoring over oceans
  4. Large-array HF imaging of bottomside ionospheric structure
     • TIDs and other phenomena
Metal Oxide Space Clouds (MOSC) Experiment

- 2 Sounding rockets sponsored by STP
  - Launched May 2013 from Kwajalein Atoll
- Release readily ionizing Samarium vapor to increase conductivity and suppress natural Rayleigh-Taylor instability causing ionospheric scintillation
- Secondary objective: investigate direct plasma impacts on RF propagation
- Ground diagnostics from 5 sites including:
  - Incoherent Scatter Radar, GPS/VHF Scintillation RXs, All-Sky Cameras, Optical Spectrograph, Ionosondes, Beacon RX, HF links
MOSC Combined Radar and Optical Measurements

- All-sky images of MOSC cloud with radar scan location superimposed
- Good tracking of cloud early on, but didn’t follow rapid westward movement well
- Even better tracking on 2nd launch
MOSC Initial Results

- Excellent radar and optical data collected from both launches
  - Multiple transects through cloud
- Plasma densities much lower than theoretical / lab predictions
- Unexpected cloud behavior (E-W elongation, separation into multiple colors)
MOSC HF Observations

- HF measurements from 5 islands (3 transmit sites, 5 receive)
- Baselines 100-350 km
  - Mostly near-vertical
- Echoes from MOSC clouds seen up to ~10 MHz
- Some apparent perturbations to propagation via background ionosphere
MOSC Analysis: Effects on Instability Development

• Pre-experiment modeling (J. Retterer, BC) suggested stabilization and descent W of cloud, destabilization and preferred plume growth to E

![Model Run](image1)

![ALTAIR radar data](image2)

• Experiment data show suggestively similar cases
• Need to fully characterize actual cloud and insert into model to determine causality
MOSC Analysis: Cloud Structure

- Model optical structure from imagery
- Correlate with radar plasma density measurements
- Obtain $N_e(x,y,z,t)$
- Use 4-D plasma density distribution to study impacts on R-T instability and RF propagation
MOSC Analysis: Spectral Measurements

• Wideband (400-900 nm) spectrograph used to monitor MOSC cloud
• Calibrated against on-site neon source
• Will be key to identifying neutral and plasma components
• Clear signature changes during early stages of release
Background Spectrum

Spectrum just prior to release...
Early Stages of Release

Initial samarium spectrum

Blue signatures stronger at beginning

Red signatures weak but discernable
Later Stable Period

Release + ~1 minute: red part of spectrum begins to dominate
Artificial Ionization Layers

- New discovery made at HAARP early in prior task
- HF heating near gyroharmonics produces artificial plasmas descending up to 100 km below F region
- Phenomenological model developed
- Structure characterized in 3-D
- Production/loss rates constrained by decay measurements
- Threshold power density determined
- Reproduction attempted at other facilities (unsuccessful, as expected based on power threshold)
- Oblique HF propagation effects demonstrated
Artificial Ionization Layer Results

1-D Model

Oblique Propagation

Production and Loss Rates

EISCAT Reproduction Attempt

3-D Structure

Loss rate fit to data after heating

Allows estimate of production rate during heating
Artificial Ionization Layers
Outstanding Science Questions

- Layer production mechanism
  - Optical signatures at 427.8 nm not clearly consistent with presumed ionizing electron flux

- Complex 3-D structure
  - Self-consistent temporal evolution of density structure and beam refraction not yet examined
  - Dominant modes in various regions

- Energy partitioning
  - Very little quantitative constraints or predictions of power absorbed by various modes/mechanisms
  - Most known effects represent ~1% power or less—surplus energy makes it difficult to rule out hypothesized processes

Image: Diagram showing energy partitioning with labels for D-Region, F Region, Heating, Acceleration, Airglow, and Ionization.
Long-Range HF Equatorial Ionospheric Radar Concept

- Utilize multi-hop HF propagation to detect ionospheric irregularities at ranges of several thousand km
  - Probes bottomside not sampled by ground-based or on-orbit sensors

- Potential backscatter features:
  - Bubble-related turbulence/gradients
  - Bottomside irregularity layers
  - Large scale density structures (direct reflection)
  - 150 km echoes
  - Electrojet echoes
  - Plasma Drifts

Raytrace showing potential coverage and echo sources for bi-directional E-W radar located near equator
Long-Range HF Equatorial Ionospheric Radar

Objectives:

- Detect and monitor equatorial ionospheric scintillation and scintillation precursors at long ranges over oceans via HF backscatter
- Directly measure HF propagation conditions
  - Island location within ~10° of magnetic equator preferred
  - Westward view could give several hours advance warning of scintillation occurrence before bubbles drift over radar site
  - Eastward view could give climatology update—sneak preview of activity at later local times
  - Monitor E-W drift = vertical electric field

Notional System:

- 16kW peak power, ~8-20 MHz
- 20 antennas on ~100’ towers
  - 16 TX/RX
  - 4 RX only
- Generally similar to SuperDARN-type radar
- Effective range: up to 4,000 km
Equatorial Propagation Geometry Relative to Magnetic Field

- Coherent backscatter requires wave vector $\vec{k}$ become perpendicular to magnetic field in region of irregularities
  - SuperDARN radars operate at high latitudes where near-horizontal propagation is nearly perpendicular to near-vertical magnetic field
  - Near the magnetic equator, any E-W path is nearly perpendicular over all elevation angles

**Backscatter possible at all elevation angles in E-W plane near magnetic equator**

Echoes at all angles in E-W plane and at multiple ranges on same rays
Echoes in Plane Perpendicular to Magnetic Field

- ALTAIR UHF radar data collected from Kwajalein Atoll, April 2013
- E-W scan perpendicular to magnetic field shows numerous bottomside backscatter regions and developing plasma depletions

**Image:**
- Background F-region ionosphere (incoherent scatter)
- Coherent backscatter from irregularities
- Plasma depletions

**Text:**
- Large variety of irregularities on bottomside associated with scintillation or scintillation precursors
HF Propagation near Plumes

- Spatially resolved near-vertical echoes from oblique soundings between Kwajalein and Rongelap atolls, Marshall Islands
- Plots cover zenith ± 40°; reflection point ~ 20° from vertical

Quiet

Plumes

Plumes

"Specular" reflection

Approximate locus of equal angles to \( \vec{B} \)

Plumes provide wide range of scattering sources and propagation paths—interpretation becomes the issue
Backscatter Power Estimates

• SNR for coherent echoes from equatorial plasma bubbles;

\[ \frac{S}{N} = \frac{P_T A_{\text{eff}} \eta}{k_b T_c} \frac{4 \pi r_e^2}{\Theta} \left( \frac{\Delta h}{r} \right)^2 \frac{3 \pi^2}{4 k^6} \frac{|\Delta N|^2}{L_0 L_1} \]

• Crude parameters;
  - \( P_t = 16 \text{kW} \)
  - \( A_{\text{eff}} = 1.4 \times 10^4 \text{ m}^2 \)
  - \( \Theta = 1/L_l \)
  - \( T = (5 \times 10^4 \text{ K})(\lambda/15 \text{ m})^{5/2} \)
  - Range bin=45km
  - 10% filled beam
  - Range=8000km
  - 10 pulse sequences per second, 30 second integrations
    - DeltaN=1e9 m\(^3\)
    - Inner scale and breaking scale per Hysell
    - 2 hops, including four D-region transits

• High SNR at night, low during day

Depending on actual \( \Delta N \) values, could potentially detect plumes out to many thousand km
Field of View and Siting Considerations

- **Field of view**
  - Approx. ±30° az
  - 4000 km range realistic
    - Some echoes at up to 8000 km?
- **Site requirements:**
  - Island or coastal site within 10° of magnetic equator
  - Power, network, ~300m x 300m area level ground
- **Potential sites:**
  - Kiritimati
  - Diego Garcia
  - Guam
  - Kwajalein
  - ….

Potential field of view if radar located on Kiritimati, Kiribati (2°N 157°W) pointed east

Potentially provides coverage over vast ocean areas
Equatorial Radar Research Challenges

• Many research questions need to be resolved before concept can be fully useful for ionospheric monitoring:
  • Elevation angle discrimination for location of irregularities and determination of propagation mode
    • Backscatter can come at any elevation angle
  • Identification of echo types and association with specific phenomena
    • Direct reflection from gradients
    • Scintillation-related spread-F
    • Bottomside/bottom-type echoes
    • Electroject/other electrodynamic processes
    • Surface scatter (propagation modes)

Large variety of irregularities on bottomside associated with scintillation or scintillation precursors
Large-Array Ionospheric Imaging Using the Long Wavelength Array

- Long Wavelength Array is a distributed array radio telescope operating in the HF and VHF bands (~10-80 MHz)
- Single station of LWA has 256 receive antennas within 100-m circle
  - Eventually planning ~40 stations across New Mexico
  - Compare with standard ionosonde: 4 receive antennas in 60-m triangle
- AFRL ionosonde at Kirtland AFB readily illuminates ionosphere within view of current and planned LWA stations
- Unique opportunity to image bottomside features such as TIDs, etc. in 2-D
- Apply superresolution to high-SNR active signals

256-element array comprising a single LWA station
Ionosonde sees all kinds of structure with only 4 antennas:
What will we see with a full 256 antenna LWA station?
Images of Transmitters at 9 MHz during White Sands HF Campaign

Multiple Transmitters at Nearby Frequencies Responsible for Bifurcated Patterns?
“Superresolution” Spatial Resolution Enhancement Techniques

- KAFB ionosonde has 4 receive antennas on 60m baseline
- Nominal angular resolution down to \(~0.1^\circ\)
- LWA station with 256 antennas and 100 m baseline should be able to do much much better

Resolution enhancement example using Kodiak SuperDARN HF ionospheric radar (T. Parris)

Resolution enhancement implemented on LWA array could provide rich ionosphere images

Direction finding of a spatially sampled plane wave (i.e. finding bearing of a radar target with a phased array radar)
Specific Objectives: Large-Array Imaging of Bottomside Structure

- Derive high-resolution point-spread functions of ionospheric reflections at near-vertical incidence from the point source represented by the Kirtland AFB ionosonde.
- Reconstruct the local ionospheric plasma density surfaces near the reflection point from the point spread functions.
- Correlate observed structures with hypothesized or observed mechanisms such as gravity waves, traveling ionospheric disturbances, large-scale gradients, etc.
- Determine which mechanisms dominate which observed modes.

Do initial data collection at solar max while 10 MHz possible.
Task Personnel

• AFRL Gov Civilians
  T. Pedersen: task lead
  E. Mishin: HF heating, ionospheric modification theory
  T. Parris: HF instrumentation, signal processing
  R. Caton: Chemical release data analysis, equatorial scintillation
  J. Holmes: optical instrumentation and analysis

• In-House Contractors
  R. Giar (SDL): Plasma modeling, HF instrumentation
  G. Taylor (UNM): LWA instrumentation and science
Summary

- New task began in October 2013
  - Continuing chemical release studies and analysis
  - Resolve lingering fundamental science issues on artificial layers
  - New look at equatorial scintillation and dynamics from long-range HF radar
  - True high-resolution 2-D RF imaging of midlatitude bottomside ionosphere with HF radio telescope using AFRL transmitter as illumination source