HF Radar for Long-Range Monitoring of Ionospheric Irregularities in the Equatorial Region

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Outline

• Current coverage of scintillation measurements
• Equatorial radar concept
• Expected propagation conditions and echo sources in the near-equatorial zone
• Radar design and performance estimates
• Fields of view and siting considerations
• Challenges
• Summary and conclusions
Christmas Island

Leoncito

Roatan

Bogota

Apiay

Piura

Ancon

Antofagasta

Santarem

Sao Luis

Alta Floresta

Cachoeira Paulistana

Cuiaba

Corrientes

Cape Verde

Ascension Island

Dakhla

Dakar

Bahrain

Qatar

Lagos

Brazzaville

Kinshasa

Bahir Dar

Djibouti

Kampala

Nairobi

Zanzibar

Darwin

Diego Garcia

Rajkot

Tirunelveli

Calcutta

Chiang Mai

Bangkok

Singapore

Taipei

Guam

Kwajalein

Baguio

Manila

Christmas Island (AUS)

Kisangani

Republic of Seychelles

Dili

Magnetic Equatorial Region Scintillation Belt

SCINDA Ground Stations
SCINDA Model

- Scintillation data collected in near real-time from global SCINDA network
- $S_4$ and ionospheric drift
- Smoothed data passed through Discrete Bubble Model (DSBMOD)
- Observed structures propagated with observed drift and decayed with empirical algorithm

Typical Scintillation Monitoring Coverage

- Ground-based scintillation monitors have limited spatial coverage
- Little “upstream” awareness
- Some “downstream” predictive capability
- In situ sensors on satellites often too high to catch many bubbles

Large areas, especially over oceans, unsampled with current techniques
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
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

System Design:

– 9.6 kW peak power, ~8-25 MHz
– 20 antennas on ~56’ towers
  • 16 TX/RX
  • 4 RX only
– Generally similar to SuperDARN-type radar
– Effective range: up to 4,000-8,000 km

Antenna array for similar system
Equatorial Propagation Geometry Relative to Magnetic Field

- Coherent backscatter requires wave vector 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.
- 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 where refraction brings Equatorial geometry.

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

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

Plumes provide wide range of scattering sources and propagation paths—interpretation becomes the issue
Equatorial HF Radar Design Specifications

- 16 antennas operating as a phased TX/RX array
- 4 antennas operating as an offset interferometer array of elevation angle determination
- 8-25MHz twin-terminated folded dipoles in corner reflectors
- 16 600W transmitters
- Receivers on each antenna to permit interferometric imaging
- Illumination beam widths 8-3 degrees
- Pulsed radar, 9.6kW peak, 10% duty cycle
- Baud widths of 40us or greater, giving 6km range resolution
- 60 degree azimuth FoV
- Ranges to 4000-8000km

Ionospheric echoes from similar system in Kodiak, Alaska

High-resolution mode

Integrated MUSIC power
Twin-Terminated Folded Dipole (TTFD) Antenna Design

Array Layout

Propagation

4 RX Interferometer

16 RX/TX

TTFD radiating element [courtesy of VT, Kevin Sterne]

Corner reflector

Photo looking down main array, interferometer in background to left

Antenna Geometry [courtesy of VT, Kevin Sterne]
Backscatter Power Estimates

- **SNR for coherent echoes from equatorial plasma bubbles;**

\[
S/N = \frac{P_t A_{\text{eff}} \eta 4 \pi r_e^2}{k_b T_c} \frac{(\Delta n)^2}{\Theta (\sigma / r)} \frac{3 \pi^2 (|\Delta N|^2)}{4 k^6} \frac{L_0 L_1}{L_2}
\]

- **Crude parameters;**
  - \( P_t = 16 \text{ kW} \) (earlier design)
  - \( A_{\text{eff}} = 1.4 \times 10^4 \text{ m}^2 \)
  - \( \Theta = 1/L_1 \)
  - \( T = (5 \times 10^4 \text{ K}) (\lambda / 15 \text{ m})^{5/2} \)
  - Range bin = 45 km
  - 10% filled beam
  - Range = 8000 km
  - 10 pulse sequences per second, 30 second integrations
  - \( \Delta N = 1 \times 10^9 \text{ m}^{-3} \)
  - Inner scale and breaking scale per Hysell
  - 2.5 hops, including five D-region transits

- High SNR at night, low during day

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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
Raytrace Calculations For Possible Site: Diego Garcia

- 10 MHz rays launched at 20° elevation toward west
- March 2013 conditions
- 16 UT = 2200

- Initial calculations suggest locus of perpendicularity too far from magnetic equator to provide reliable backscatter.
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
Summary

Long-range HF radar under development to test potential for remote scintillation monitoring over oceans

- Hardware similar to SuperDARN-type systems
- Potential to receive echoes out to 4000+ km
- Single system could potentially cover an entire ocean
- Propagation geometry very different
- Large number of potential echo sources associated with plasma bubbles or precursor phenomena
- Many challenges
  - Elevation angle resolution to discriminate propagation modes
  - Identification of echo types with specific phenomena