Air Force Research Laboratory

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

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Space Weather Center of Excellence

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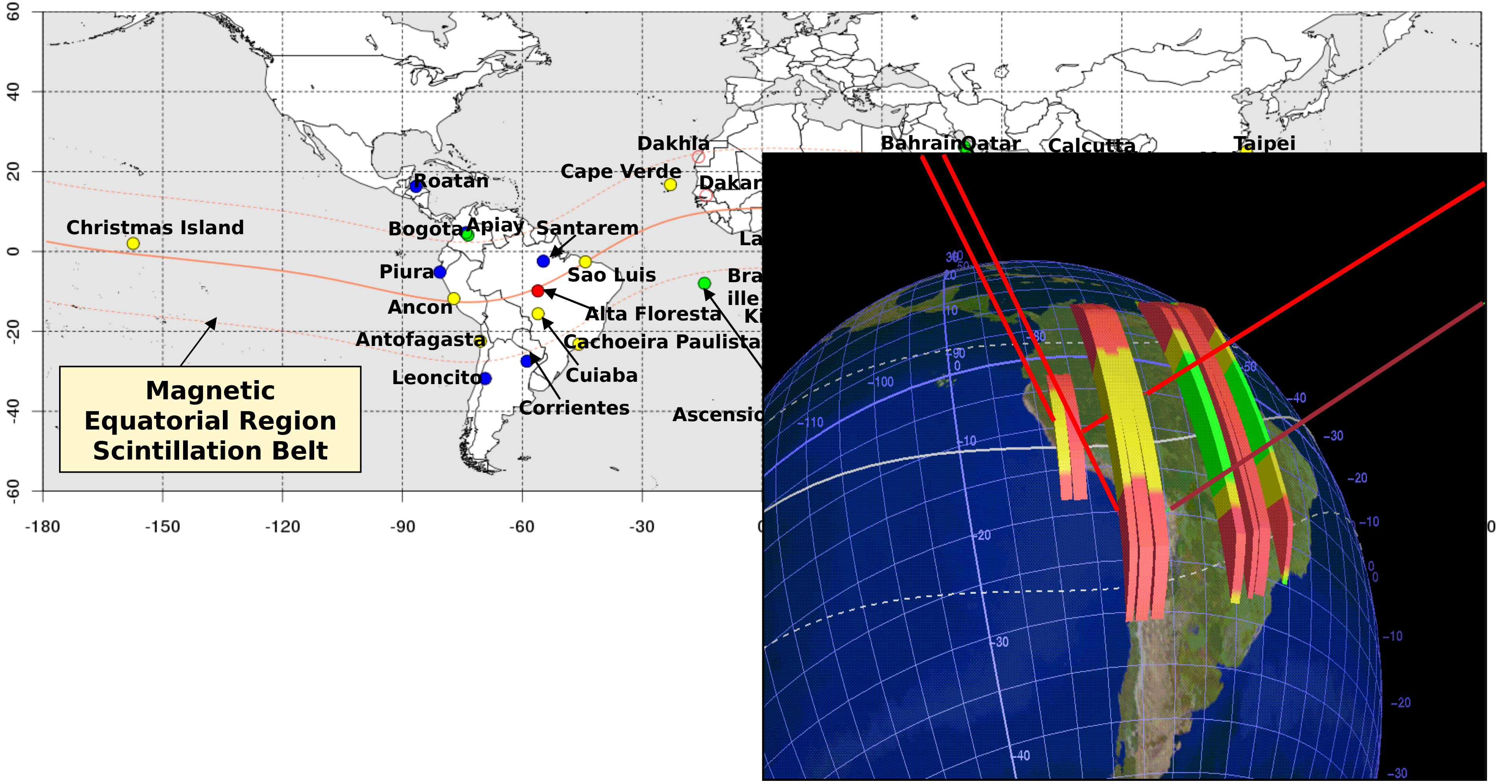
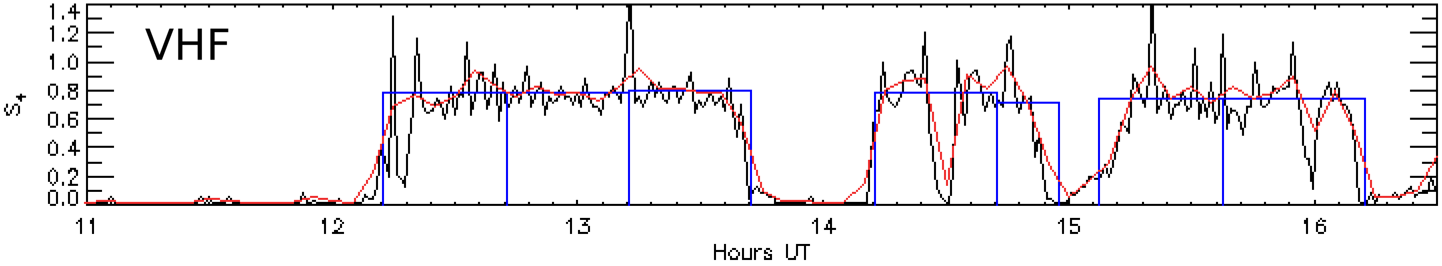
Outline

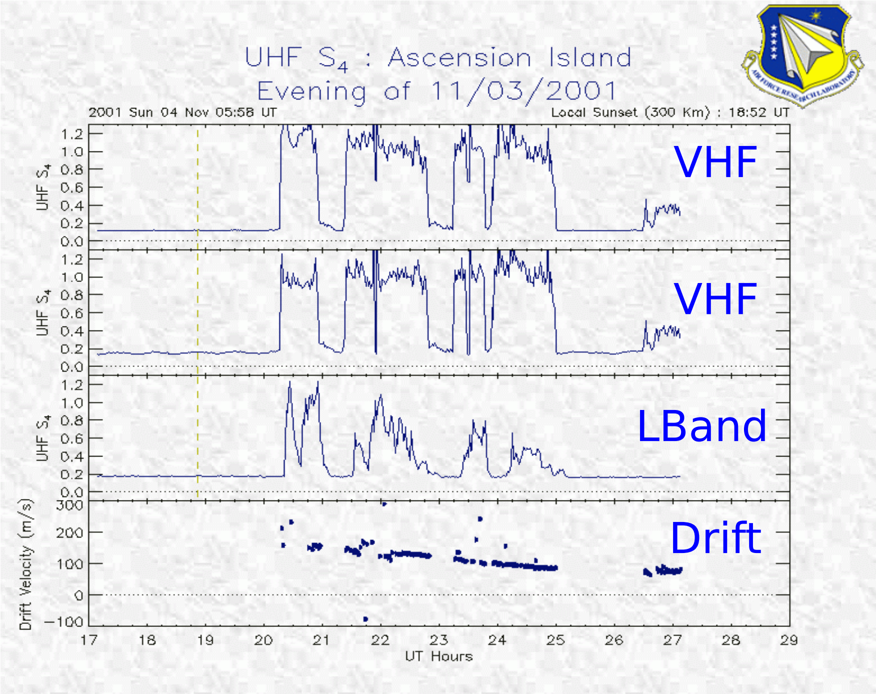
- Current coverage of scintillation measurements
- Equatorial radar concept
- Expected propagation conditions and echo sources in the near-equatorial zone
- Radar design and performance estimates
- Fields of view and siting considerations
- Challenges

SCINDA Ground Stations



SCINDA Model





SCINDA Model

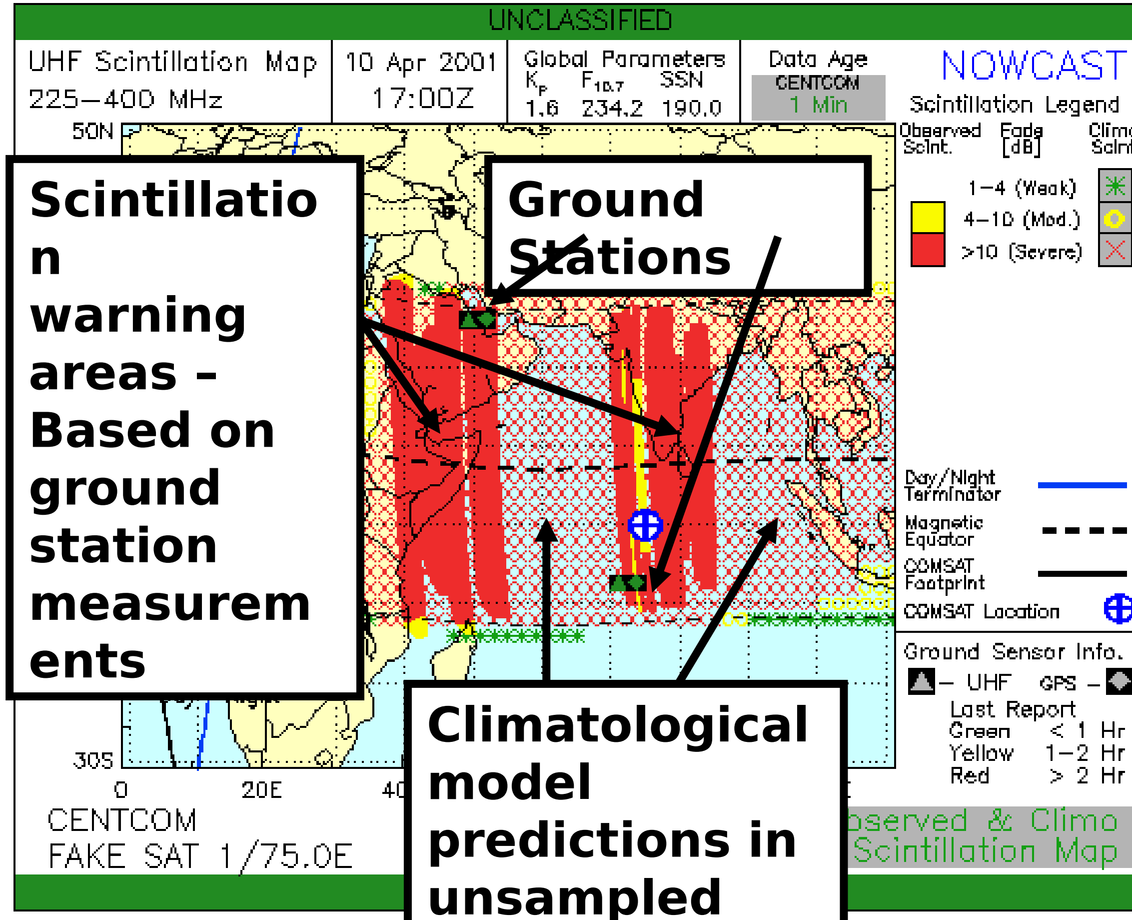
- Scintillation data collected in near real-time from global SCINDA network
- S_4 and ionospheric drift
- Smoothed data passed through Discrete Bubble Model (DSBMOD)
- Observed structures propagated with observed drift and decayed with empirical algorithm

Groves, K.M., et al., Equatorial scintillation and systems support, *Radio Sci., 32,* 2047, 1997.

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

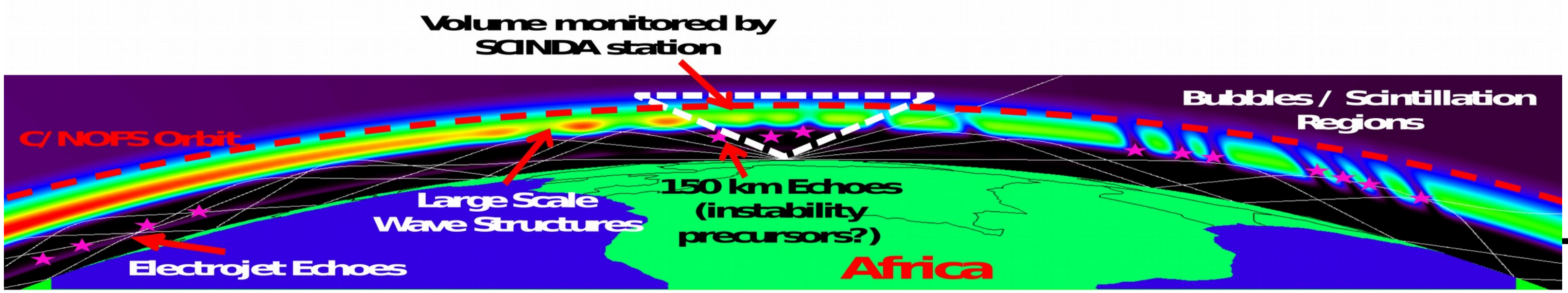


Large areas, especially over oceans, unsampled with current techniques

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**

Raytrace showing



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 $\vec{k}$ 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

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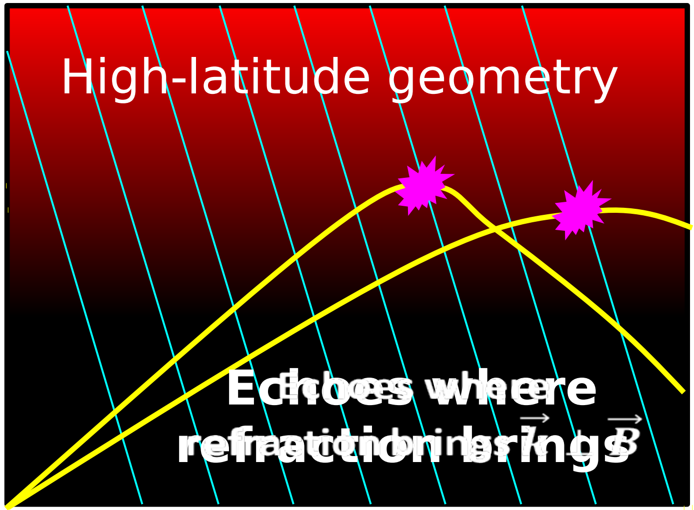
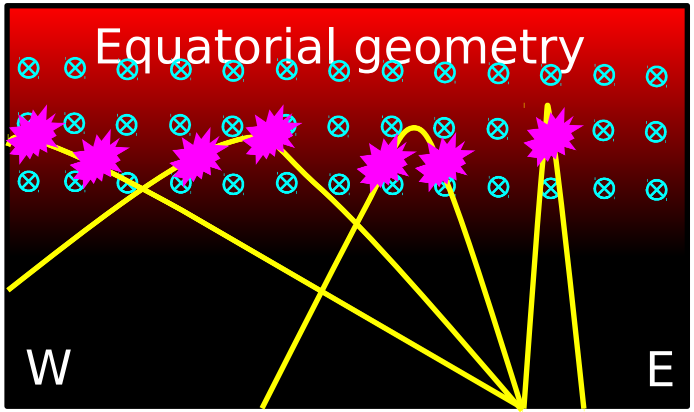
Backscatter possible at all elevation angles in E-W plane near magnetic equator

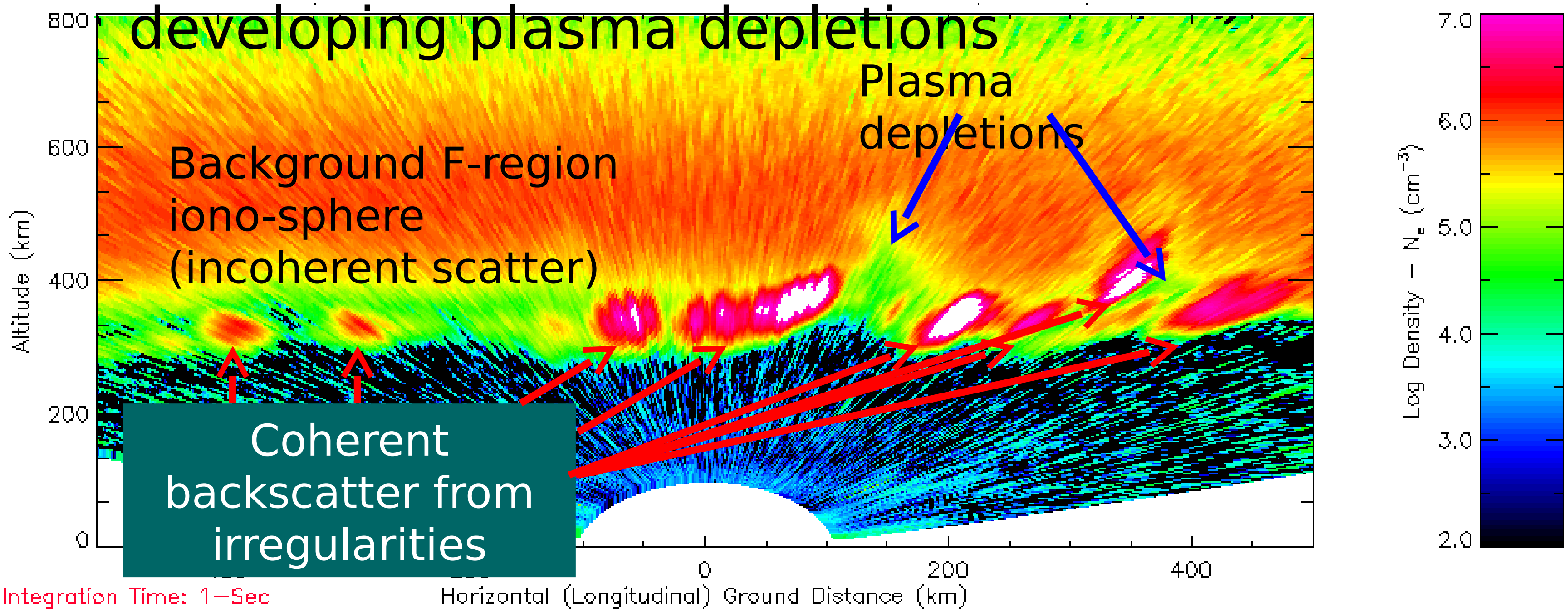




Echoes at all angles in E-W plane
and at multiple ranges on same rays

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

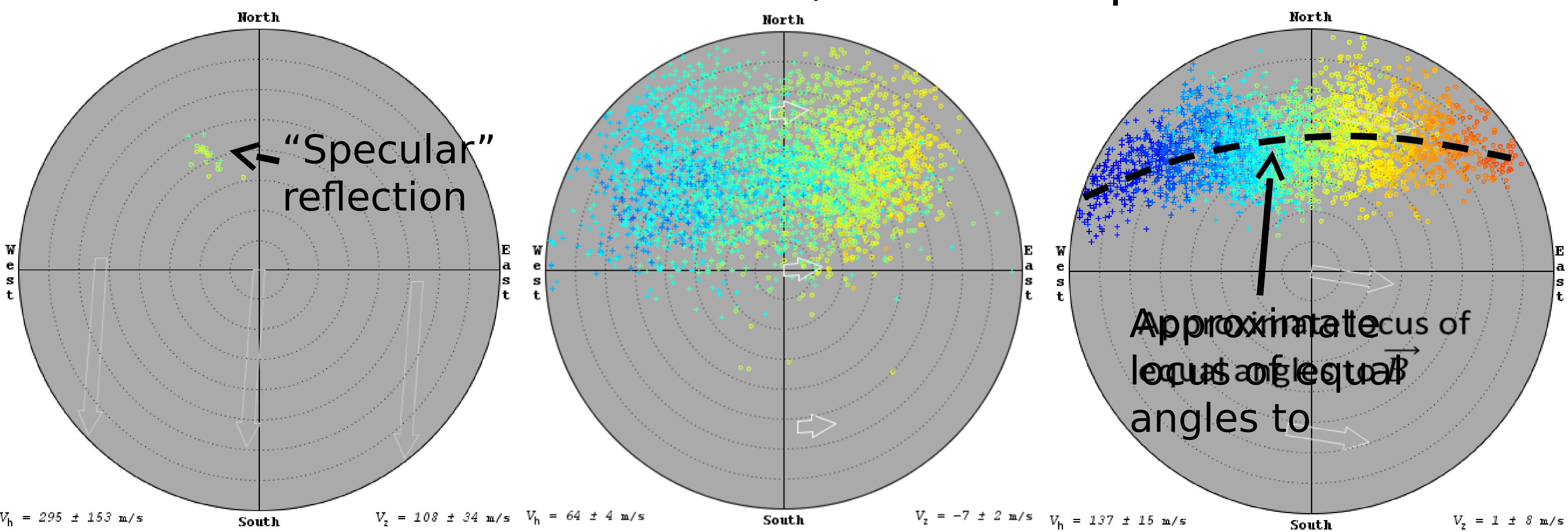


Large variety of irregularities on bottomside associated with scintillation or scintillation precursors

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

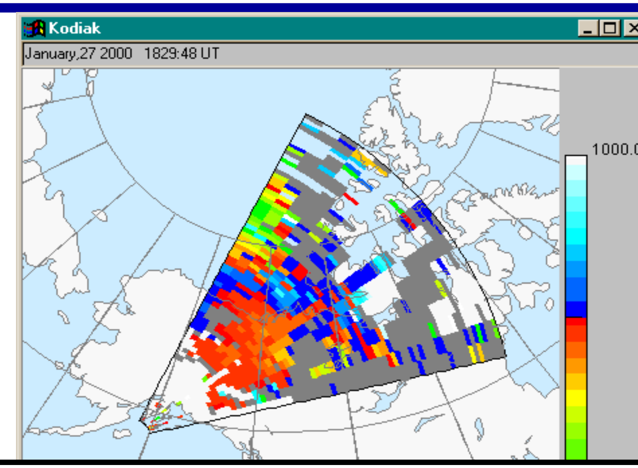
Quiet Plumes Plumes



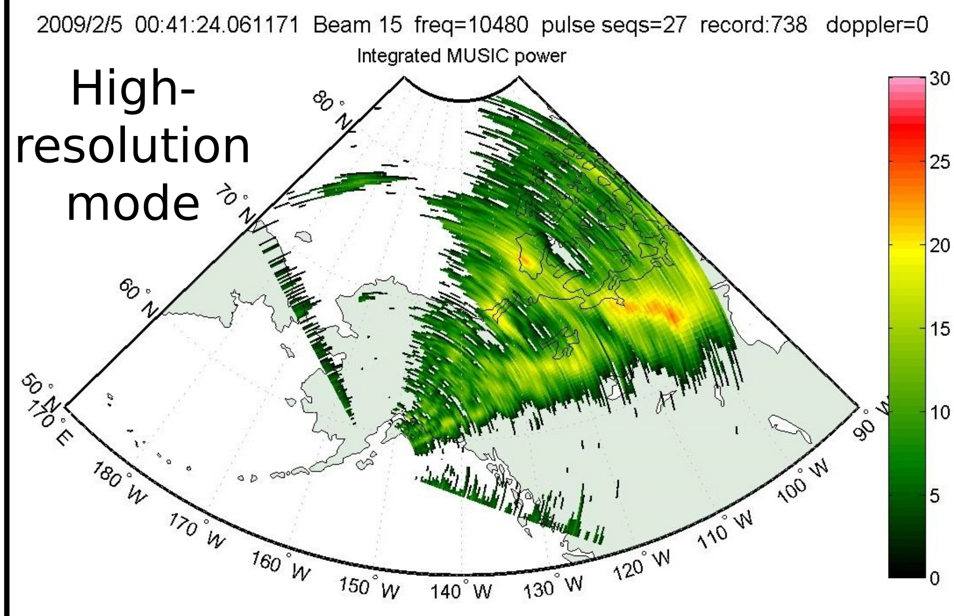
Plumes provide wide range of scattering sources and propagation paths—interpretation becomes the issue

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

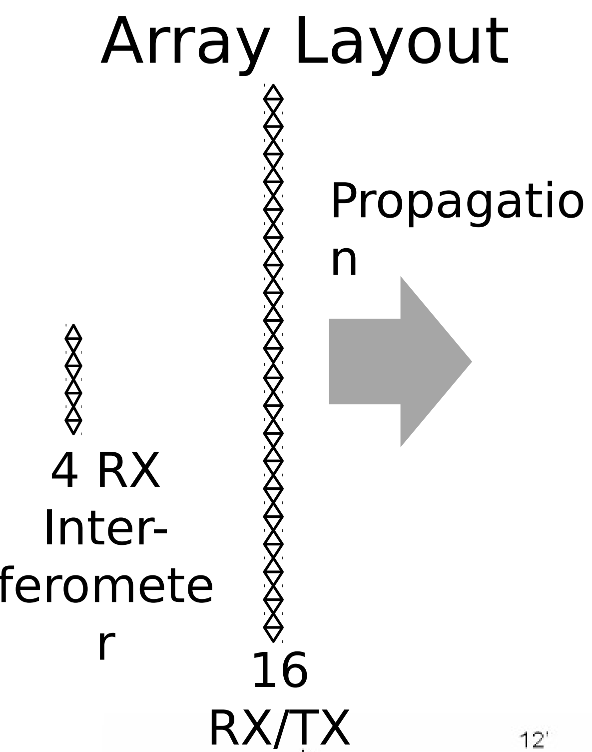


Ionospheric echoes from similar system in Kodiak, Alaska



High-resolution mode

Twin-Terminated Folded Dipole (TTFD) Antenna Design



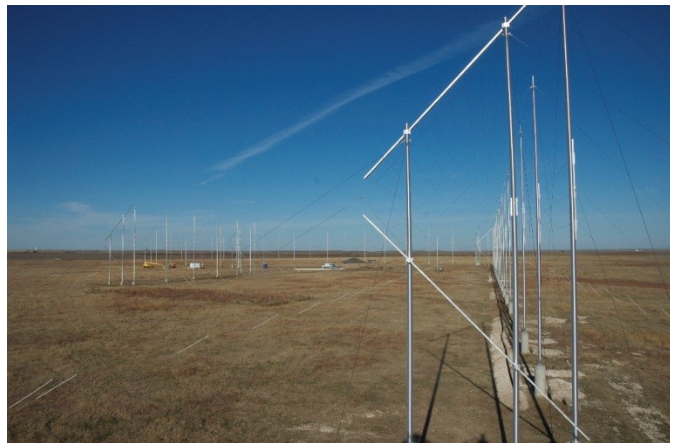
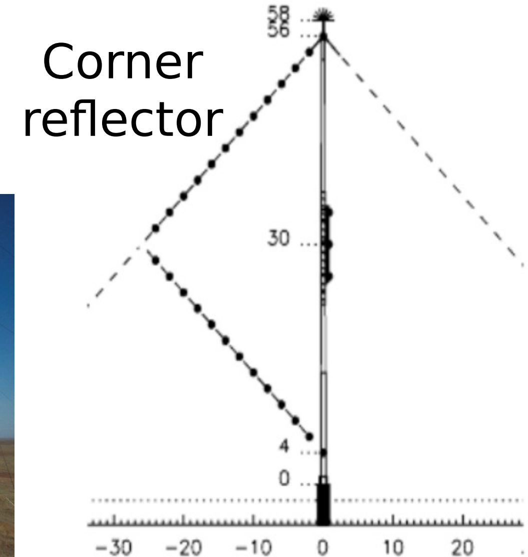
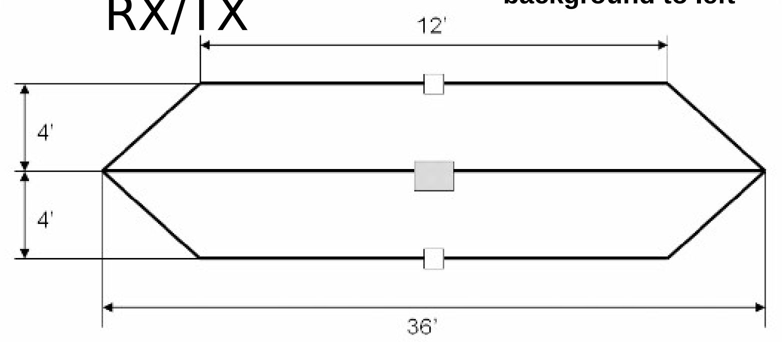
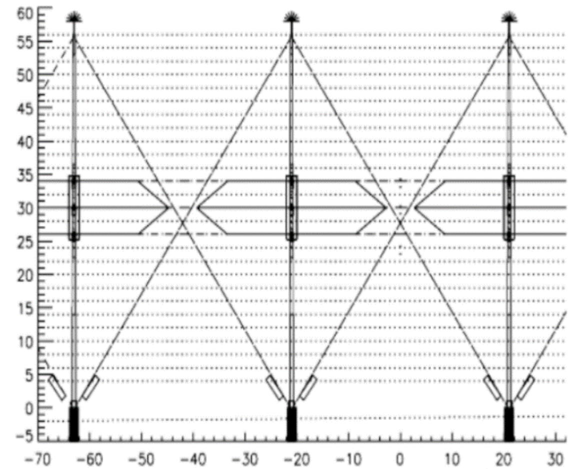


Photo looking down main array, interferometer in background to left





TTFD radiating element [courtesy of VT, Kevin Sterne]



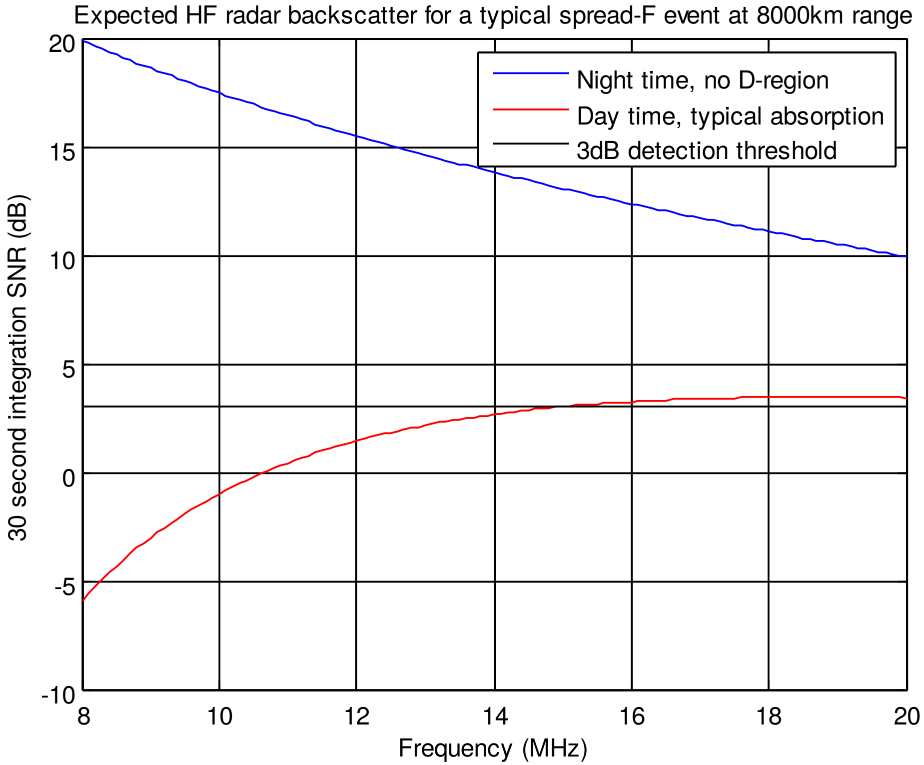
Antenna Geometry [courtesy of VT, Kevin Sterne]

Backscatter Power Estimates

- SNR for coherent echoes from equatorial plasma bubbles;

$$\frac{S}{N} = \frac{P_T A_{eff}\eta}{k_b T c}\frac{4\pi r_e^2}{\Theta}\left(\frac{\Delta h}{r}\right)^2 \frac{3\pi^2}{4k^6}\frac{\langle|\Delta N|^2\rangle}{L_0 L_1}$$

- Crude parameters;
  - P_t=16kW (*earlier design*)
  - A_{eff}=1.4e4 m^2
  - Θ=1/L_l
  - $T = (5x10^4\ K)(\lambda/15\ m)^{5/2}$
  - 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
  - 2.5 hops, including five D-region transits
- High SNR at night, low during day

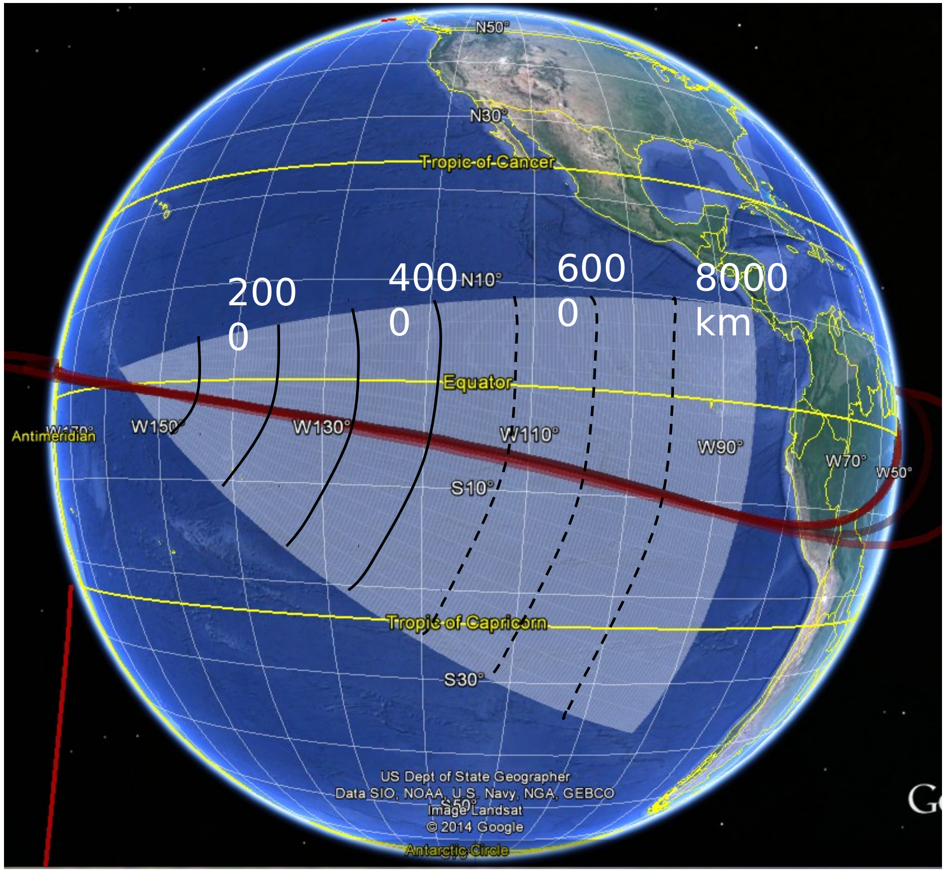


Depending on actual *ΔN* values, could potentially detect plumes out to many thousand km

- High SNR at night, low during day

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
    - ….

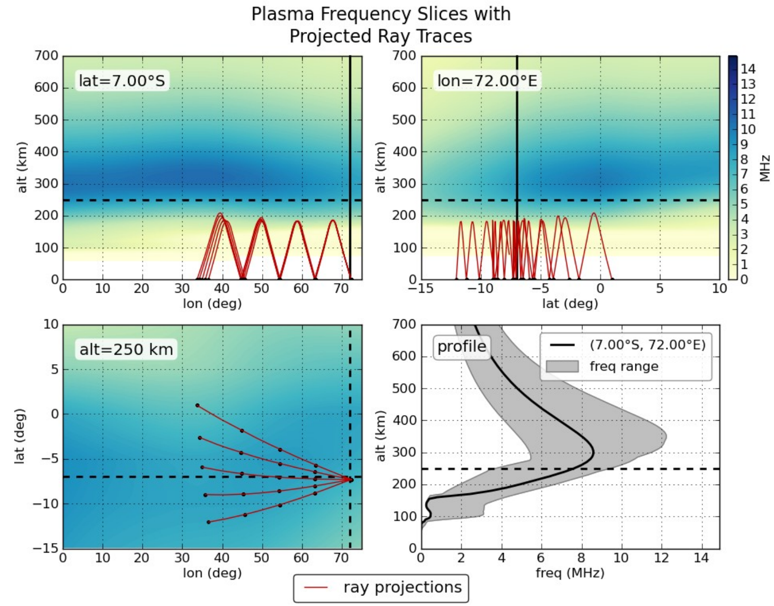


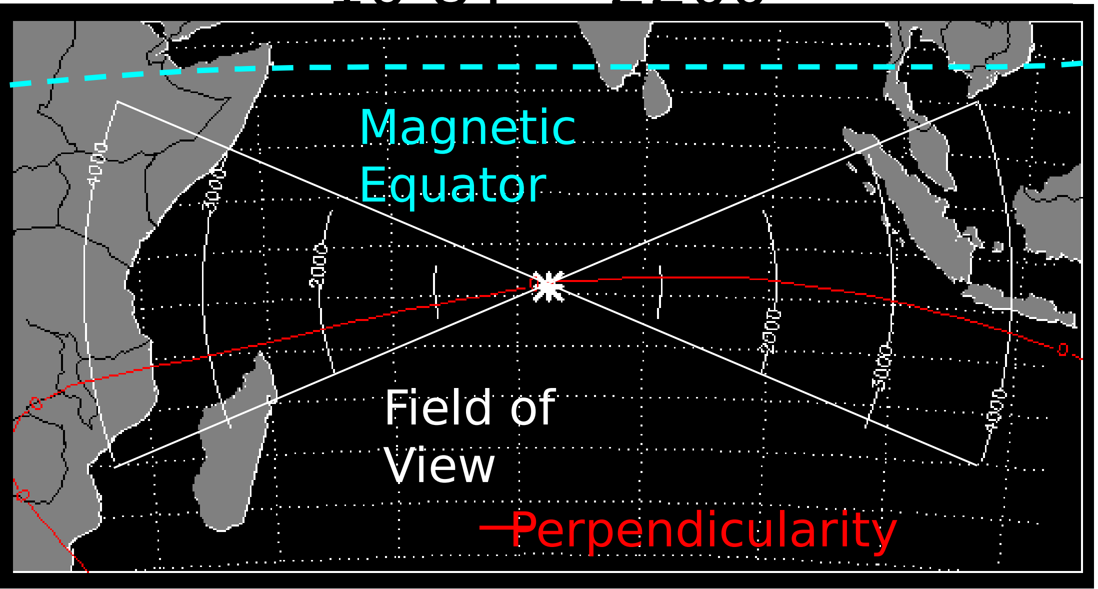
Potential field of view if radar located on Kiritimati, Kiribati (2°N 157°W) pointed east

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**