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High Frequency Geolocation and System Characterization (HFGeo)

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Frank C. Robey, D.Sc.

HFGeo Phase 1B Proposers' Day Briefing,

July 13, 2012

Agenda

8:00 – 8:30 am	*Check-in*	
8:30 – 8:40 am	*IARPA Overview and Remarks*	Dr. Peter Highnam IARPA Director (acting)
8:40 – 9:10 am	*Contracting Officer Remarks*	Ms. Sarah Wiley IARPA Contracting Officer
9:10 – 10:30 am	*HFGeo Phase 1B Overview*	Dr. Frank Robey SC Deputy / Program Manager
10:30 – 10:45 am	*Break*	
10:45 – 11:30 pm	*HFGeo Phase 1B T&E*	Dr. Frank Robey SC Deputy / Program Manager
11:30 – 12:00 pm	*Q&A Session*	
12:00 – 12:45 pm	*No Host Lunch*	
12:45 – 3:00 pm	*Capability Briefings and Informal Teaming Discussions*	Non-Government Personnel Only

Outline

- Introduction
  - Proposers' Day goals
  - Program Overview
  - Single Site Location (SSL) and the Ionosphere
- Technical Approach
- Metrics and Schedule
- Administrative

Disclaimer

- **This presentation is provided solely for information and planning purposes**
- **The Proposers' Day Conference does not constitute a formal solicitation for proposals or proposal abstracts**
- **Nothing said at Proposers' Day changes the requirements set forth in a BAA**
- **BAA supersedes anything presented or said at the Proposers' Day**

Proposers' Day Goals

- Familiarize participants with IARPA's interest in characterization and modeling of the Ionosphere

- Please ask questions & provide feedback; this is your chance to alter the course of events.

Schedule

- **Once the BAA is released, questions can only be answered in writing on the program website**
- **Proposals will be due 45 days after the BAA is released**

High Frequency (HF) Intelligence Missions

Radar characterization

What is this radar doing?

HF Source Geolocation

Where is this transmitter?

- **HF use has advanced significantly in last 20 years**
  - **Low entry cost relative to satellites**
  - **Ease of use with modern technology**
- **Program goal is >10X improvement in geolocation accuracy**

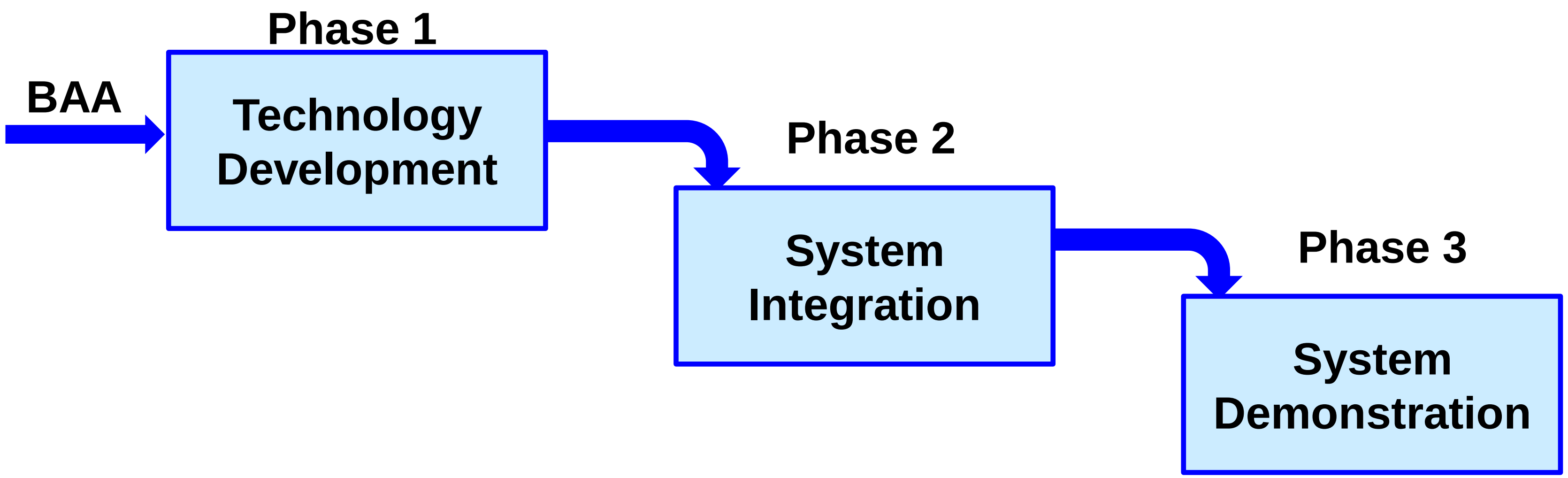
This multi-phased program will develop technology to address geolocation and characterization of HF sources

Array on dike: http://ifmaxp1.ifm.uni-hamburg.de/ANT_PET_1_100DPI.shtml

Antenna from: http://www.hamuniverse.com/ae5jufielddayantenna.html

HFGeo Program

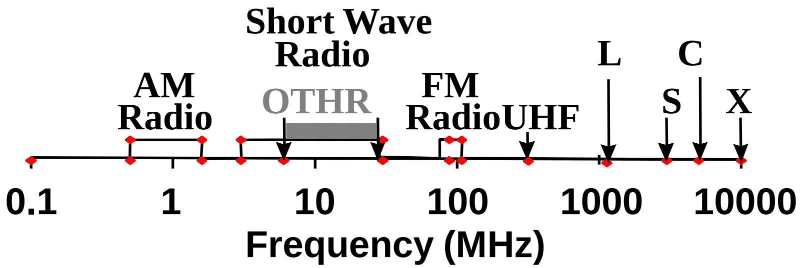
- **Phase 1: HF technology development** — Focus of this effort
  - **Ionosphere: Accurate ionospheric understanding**
  - **Antenna: Small, low infrastructure antenna systems**
  - **Signal Processing: Sort desired signals from noise and determine propagation modes**
- **Phases 2 and 3: System integration and demonstration**
  - **Performance Metrics to be determined based on the results of Phase 1**
  - **Transition from “component” technology to system development**

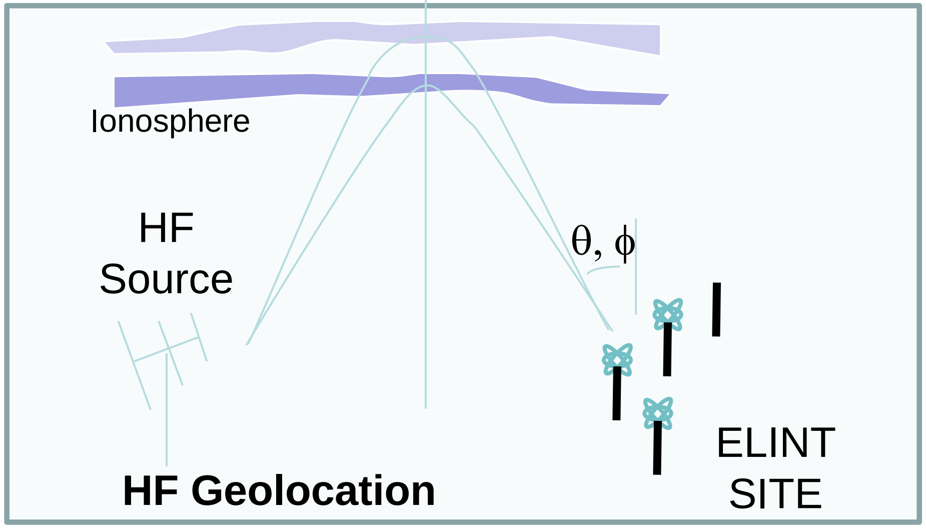


Single Site Location (SSL) and the Ionosphere

Single Site Location (SSL)

- Accurate single-site geolocation has long been an HF Electronic Intelligence (ELINT) goal
- SSL relies on azimuth and elevation measurements at the ELINT site
- The measured angles are back-propagated through an ionospheric model to obtain a location on the ground
- Accurate ionospheric modeling is key to accurate SSL

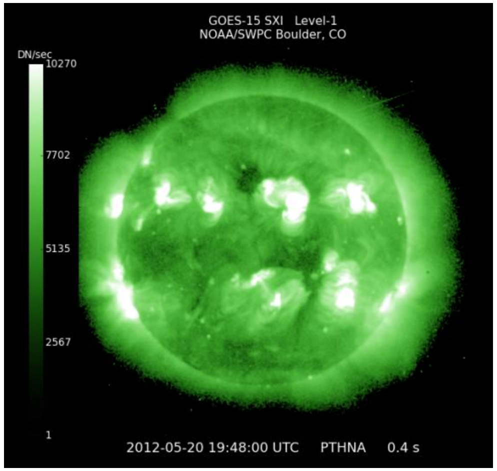




Origin of the Ionosphere

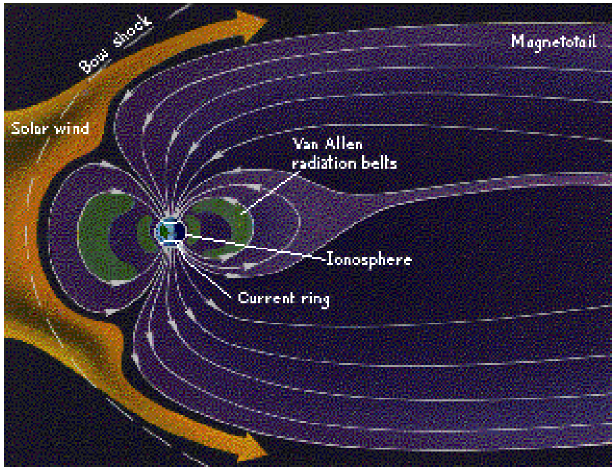
- **Solar EM radiation dominates ionization of low-density atmospheric components at high altitudes**
- **Solar wind interacts with the upper atmosphere**
- **Earth's magnetic field plays a large role in movement of free electrons**

Sun weather



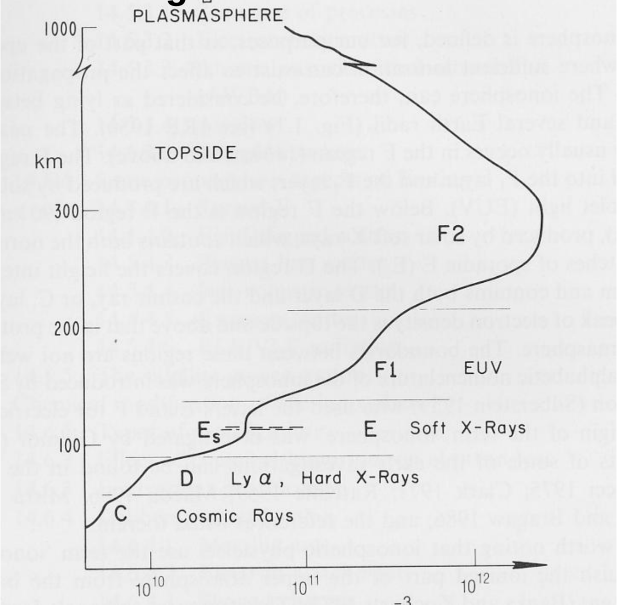
http://www.swpc.noaa.gov/sxi/images/latest_sxi.png

Interaction at the Earth



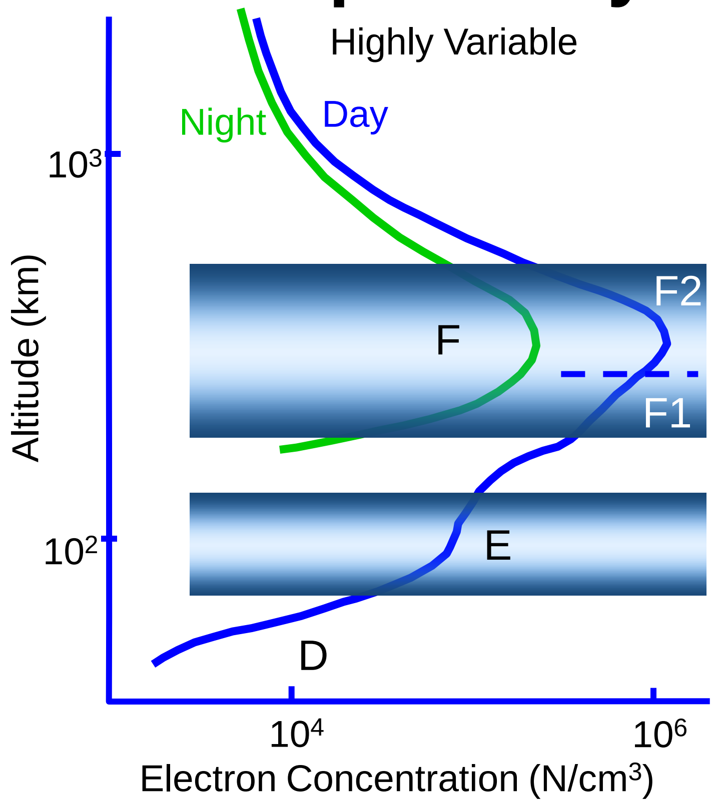
Solar/earth interaction from :http://fusedweb.llnl.gov/cpep/chart_pages/5.plasmas/solarwind.html

Ionizing radiation interactions

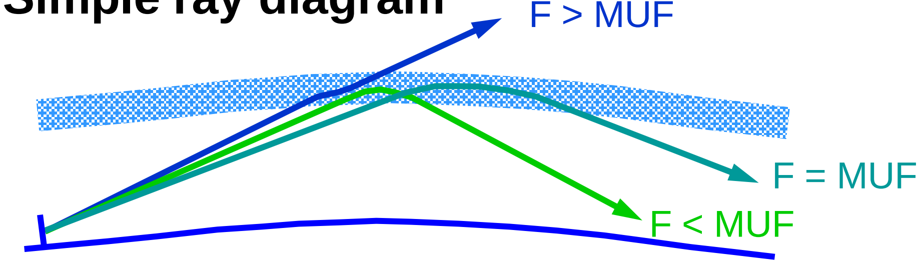


Electron Density (m^{-3})

Ionosphere Dynamics and HF Propagation



Simple ray diagram



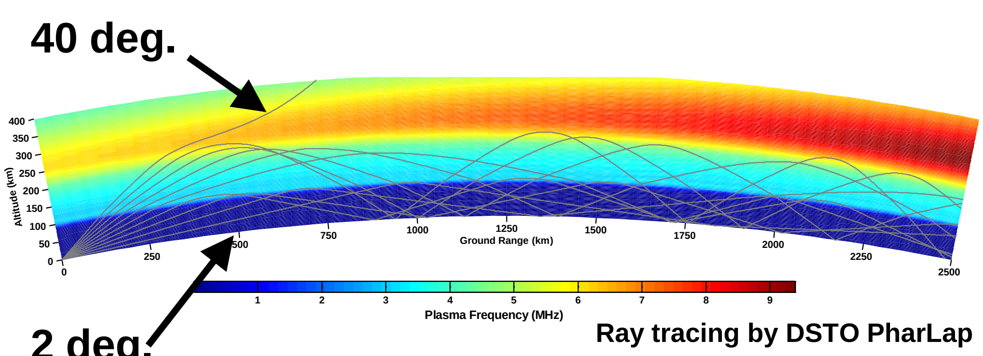
Variable nature impacts refraction

Critical / plasma frequency $f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_0}}$

MUF = Maximum Usable Frequency
(secant of incidence angle * f_p)

Complex ray diagram

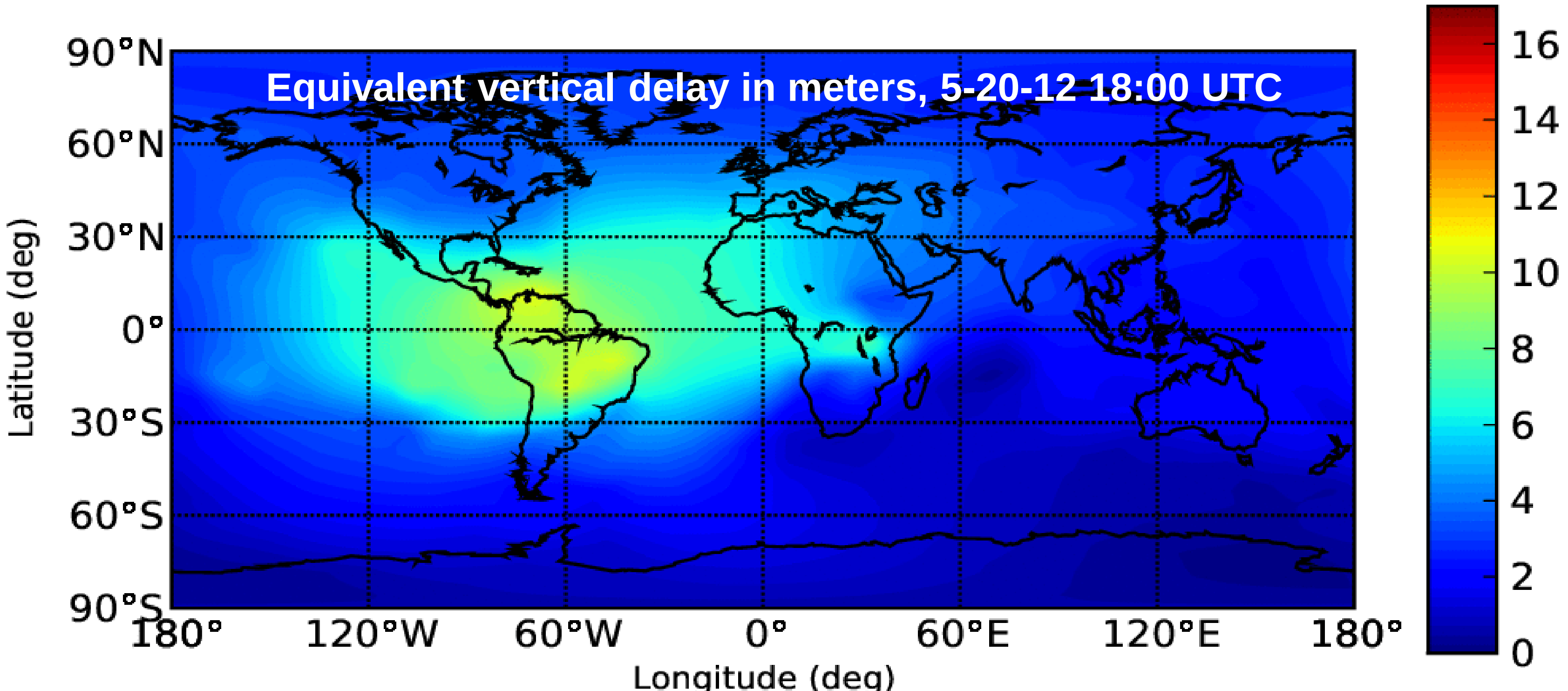
(Rays launched from VA toward Puerto Rico (10 MHz, Afternoon))



Ray tracing by DSTO PharLap

Ionospheric Measurement Example

- **Important parameter between ground & space is total electron content, or equivalently, additional signal delay**
- **Determines corrections to GPS systems**

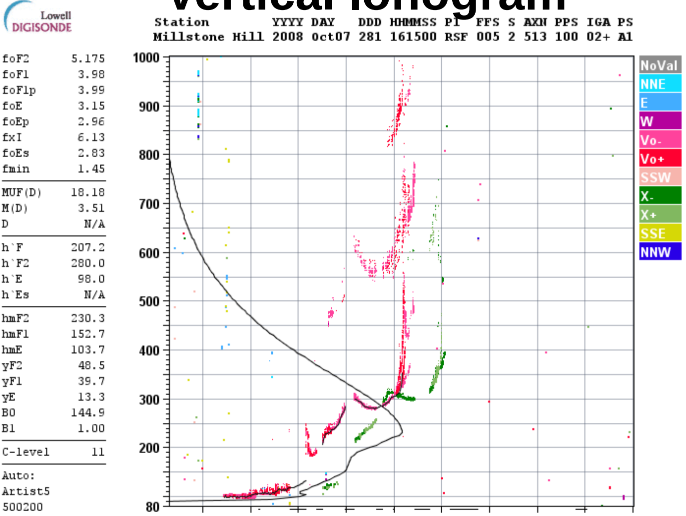


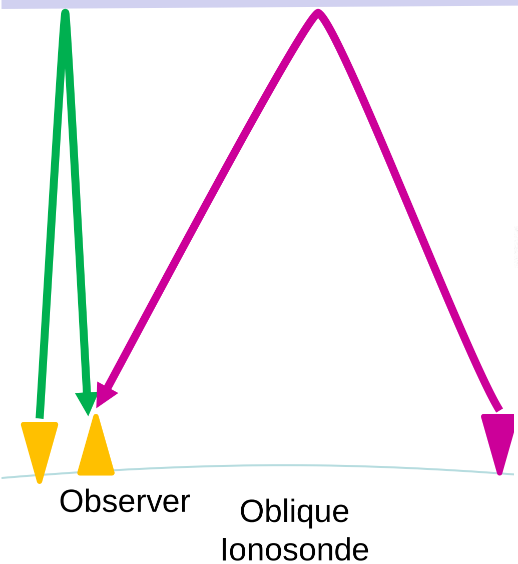
http://www.gdgps.net/products/tec-maps.html

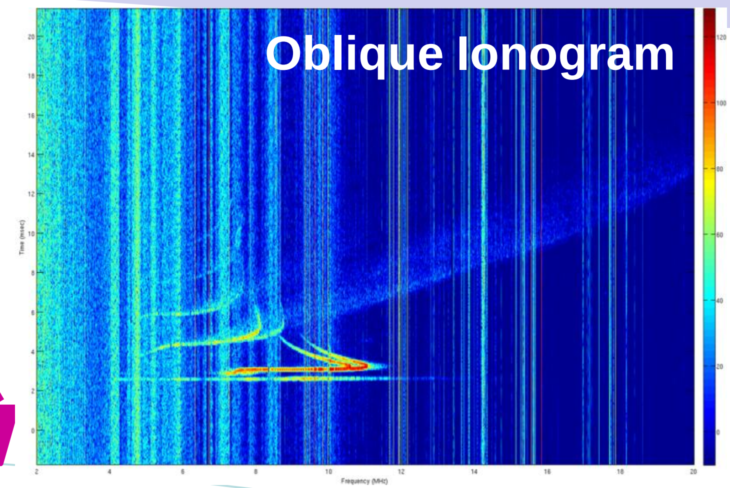
Ionospheric Measurement

- Vertical and oblique ionosonde are the reference standards for bottom-side ionospheric understanding
- There are insufficient numbers and density
- Known reference points at fixed frequencies provide excellent information on ionospheric motion

Vertical Ionogram



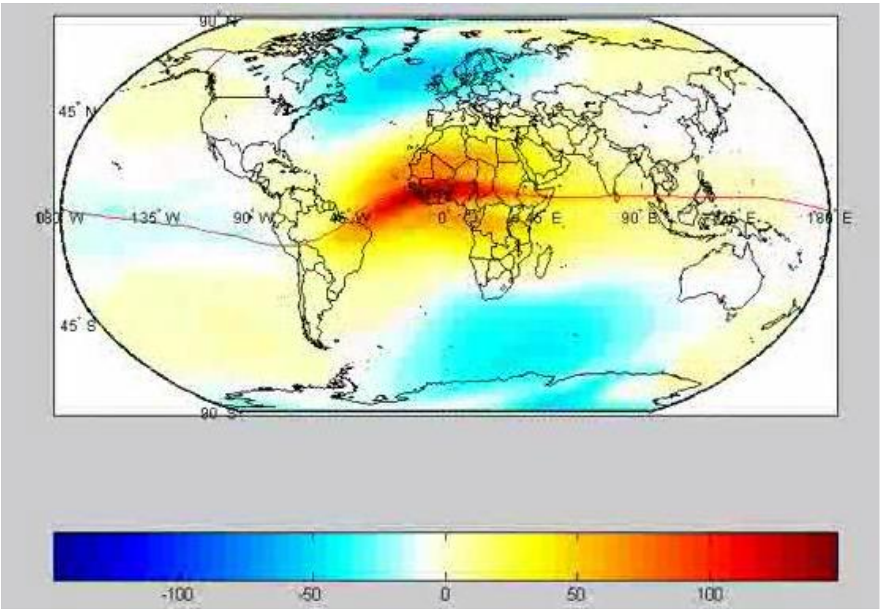




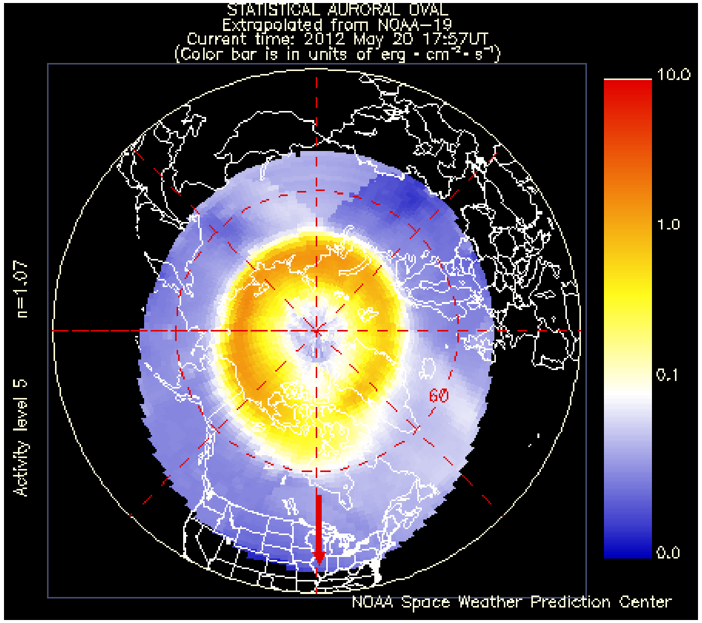
Lowell digisonde data from:
http://car.uml.edu/common/DIDBYearListForStation?ursiCode=MHJ45

Why Tropical/Mid-latitude Now?

- **Global bottom-side ionospheric model is noble long-term goal**
- **Auroral and equatorial regions are disturbed by electrojet phenomena**
  - **Induces high ionospheric turbulence making measurement & modeling much more difficult**
  - **Turbulence propagates into mid-latitudes as Traveling Ionospheric Disturbances (TID)**
- **HFGeo will first solve a simpler problem focusing on tropical/mid-latitudes**



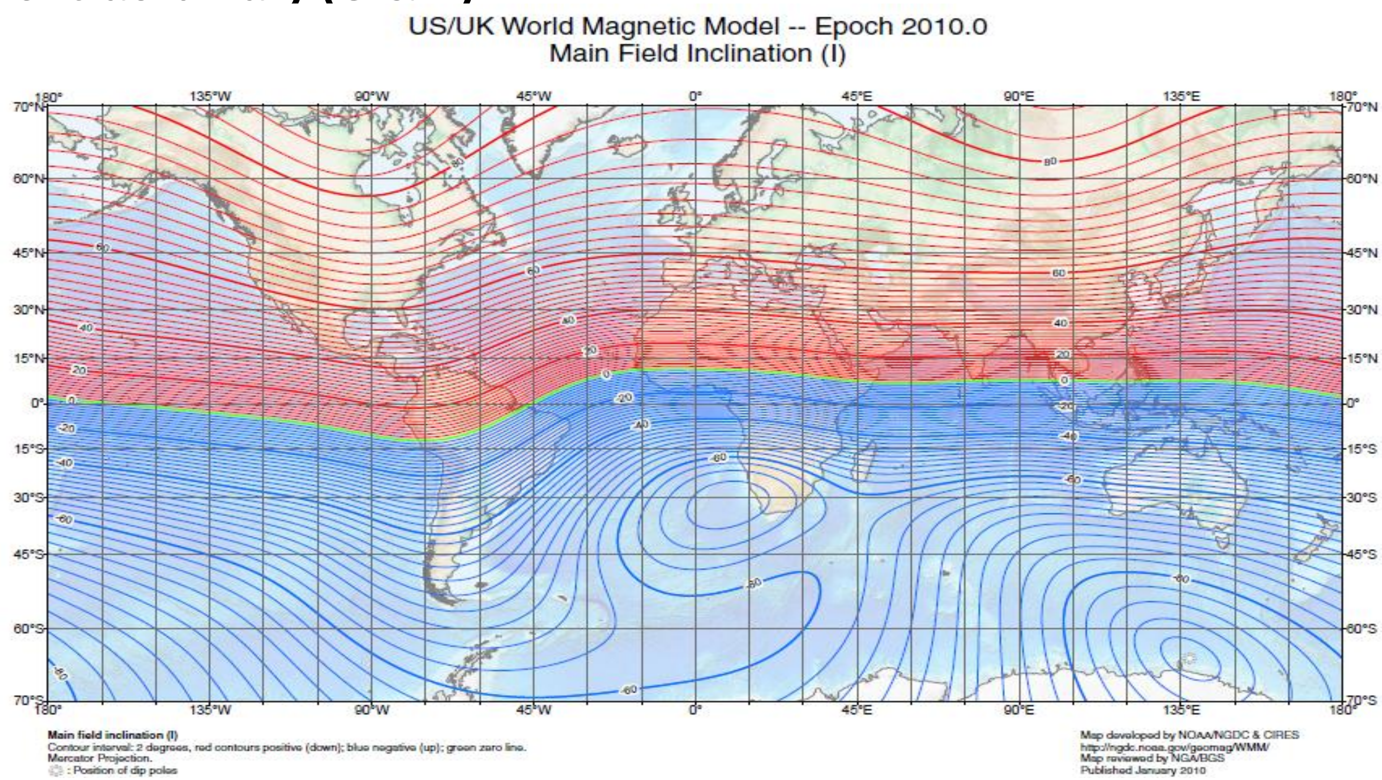
http://en.wikipedia.org/wiki/Equatorial_electrojet



http://www.swpc.noaa.gov/pmap/pmapN.html

Geomagnetic effects

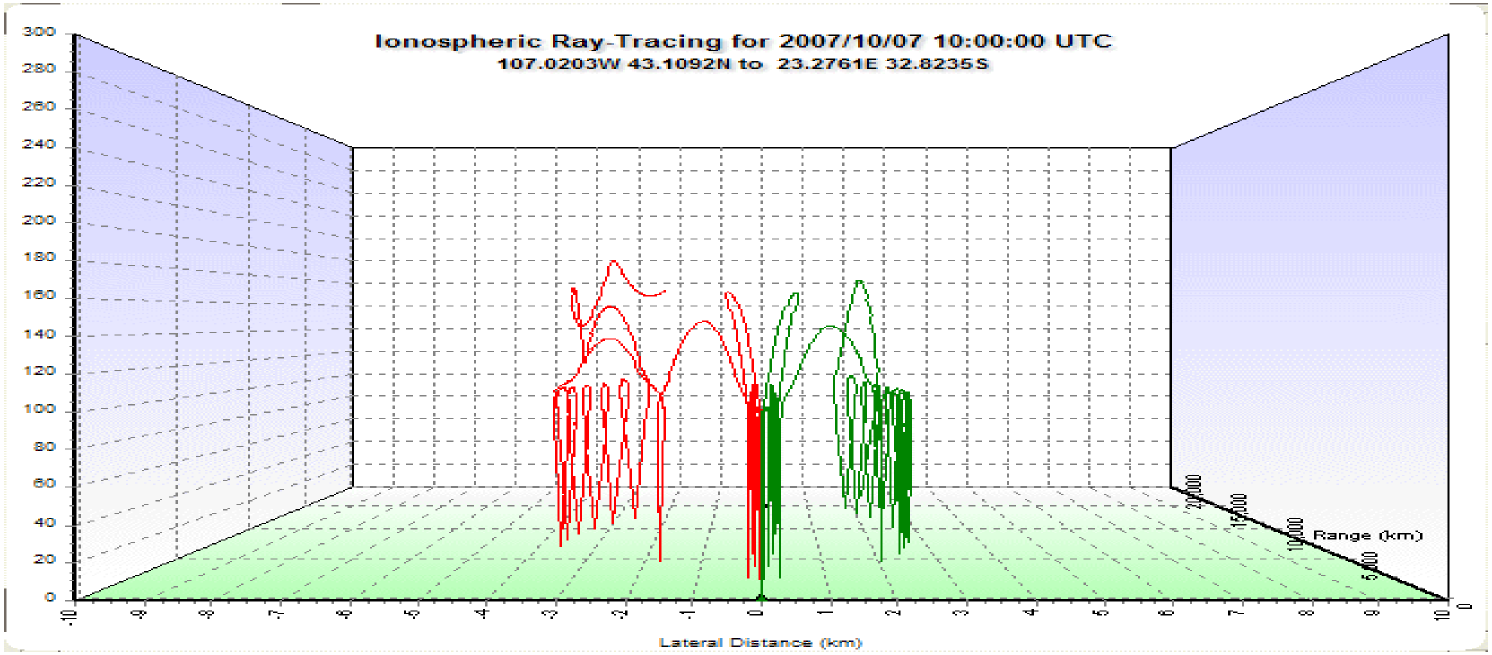
- **Earth's magnetic field interacts with HF rays and ionosphere to produce**
  - **Large currents**
  - **Splitting of HF signals into two ray paths termed Ordinary and eXtraordinary (O & X)**



http://www.ngdc.noaa.gov/geomag/WMM/image.shtml

O and X Ray Paths

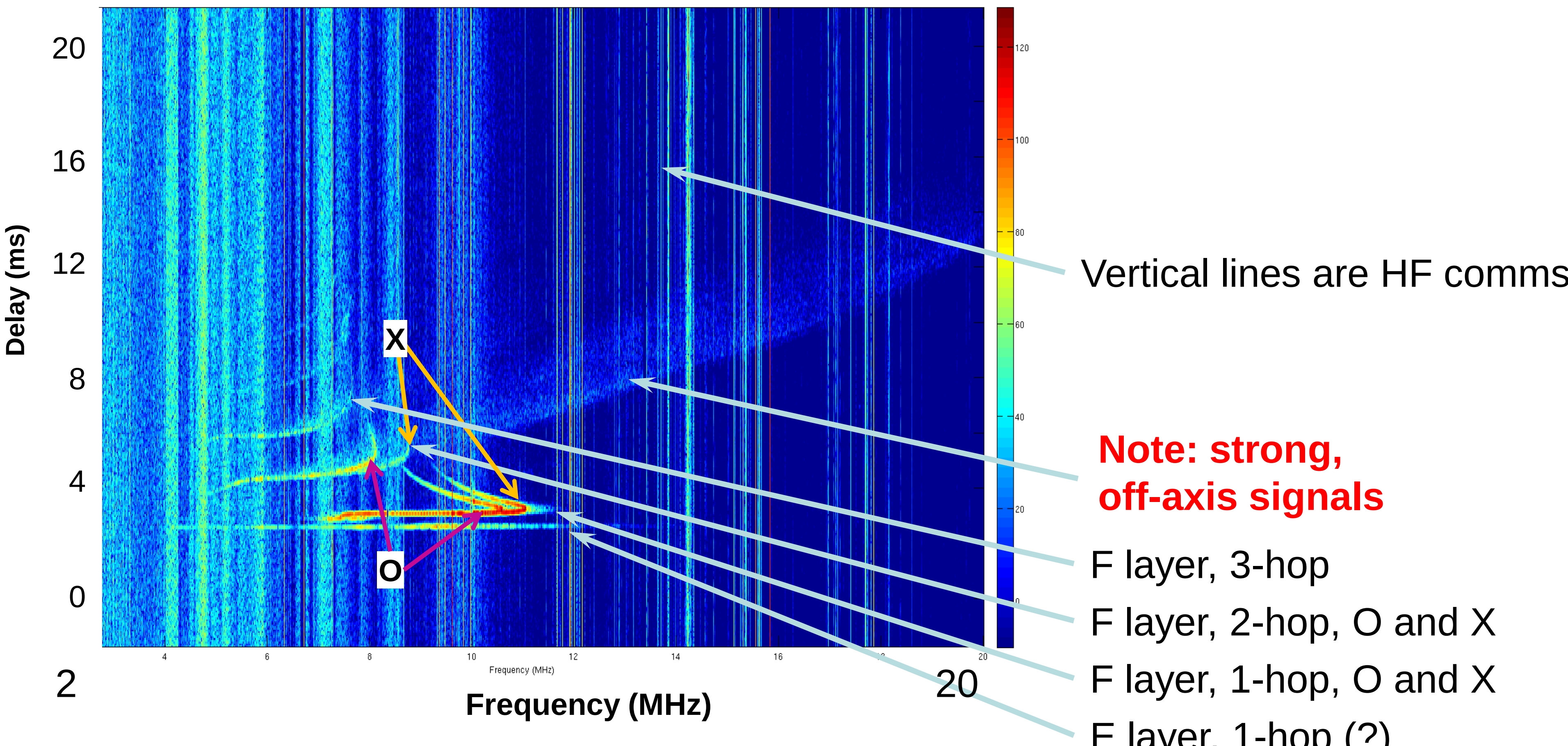
- Electrons precess around magnetic field lines (gyrotron motion)
- Signal splits due to differences in propagation velocity for ~right and ~left circular waves



Ray tracing by Proplab-pro: http://www.spacew.com/proplab/

Oblique Ionogram Example

New Kent, VA to Bedford, MA



Outline

- **Introduction**
- **Technical Approach**
  - **Black box**
  - **Previous work and differences**
  - **Development approach**
- **Metrics and Schedule**
- **Administrative**

Black Box Approach to Ionospheric Modeling

To obtain a model most pertinent to HF Communications, judge it by how well bottom side phenomena are reproduced. All else is internal.

Inputs → **Ionospheric Module** → Outputs

Inputs

Real-time
- Sensor data & metadata,
- SSN, Kp, etc.

A-priori
- IRI
- Global Magnetic Model (GMM)
- DTED

Ionospheric Module

Services
Magneto-ionic Ray Tracing
Channel model generation
Vertical/oblique Ionogram Generation

Internal Model
Sensor data to iono model inversion
Assimilation
Interpolation/ Extrapolation/ Regularization
Iono weather propagation

Outputs
-Ray trace
-Simulated Ionograms
- Ray deflection
-Channel Model Diagnostics
- Fit quality
- Model visualizer
- etc.

Previous work

Many ionospheric developments have occurred. Some are ongoing

- **Models (International Reference Ionosphere (IRI), Chapman, etc.)**
- **Ray tracing Codes (Jones-Stevenson)**
- **Remote sensing methods**
- **Inversion and scaling methods (ARTIST, CREDO, etc.)**
- **Space weather indices (Sunspot number (SSN), scintillation KP, etc)**
- **Forecasting technologies (e.g., EU-COST-Actions, C/NOFS)**
- **Data assimilation methods (GAIM, GIRO, TRIPL-DA, GPSII etc.)**
- **Physics-based coupling transport, electrodynamics (CEDAR, SCINDA, FIRST, etc.)**
- **Global magnetic model 2010**

So, what is different?

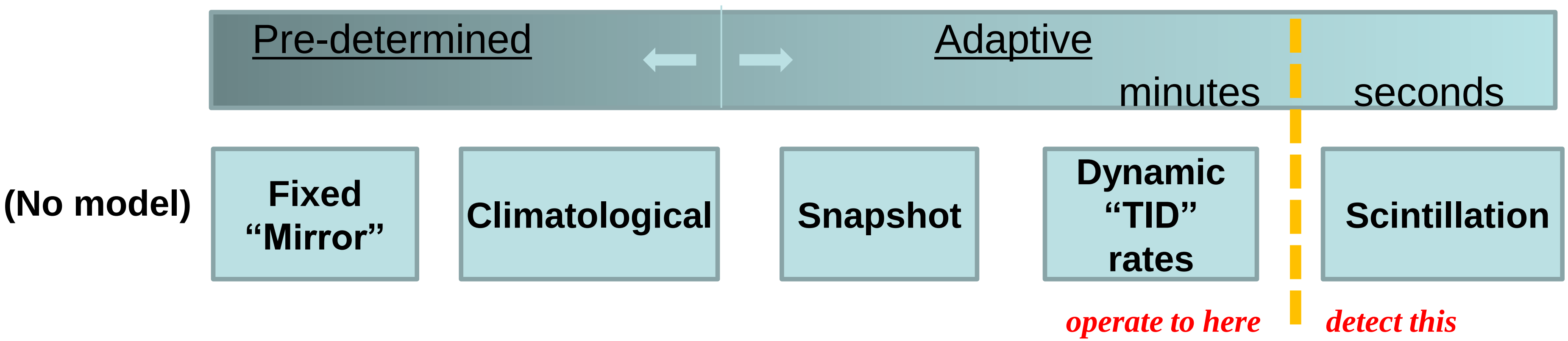
Differences from previous work

- HFGeo focus is on regional/wide area bottom side profile rather than global total electron content (TEC) or local profile
- Model accuracy metrics that are directly relevant to HF communication
  - Considers ionospheric accuracy impact on HF ray-path propagation
  - Required level of fidelity (10x SSL geolocation accuracy)
- Dynamic real-time rather than climatological modeling
  - Intended to capture the minute-by-minute changes
- Focus is on nowcast & backcast rather than forecast
- Assimilation of sources that have been kept distinct
  - Known reference points (KRP), beacon, ionosondes, GPS

Ionospheric Model Spectrum

What is meant by a dynamic model?

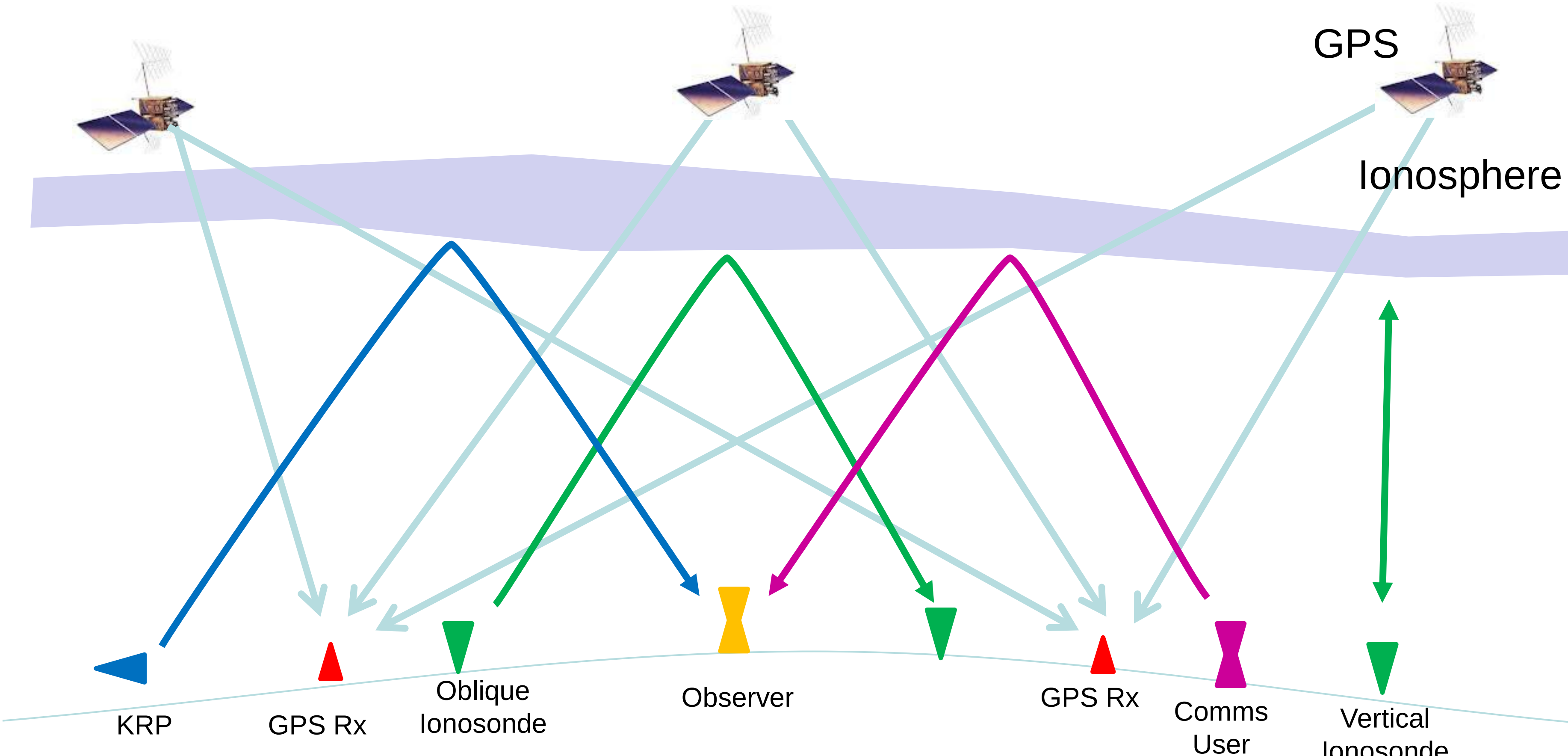
Modeling Scale



- **There are multiple levels of potential spatial / temporal scales for the measurement & modeling**
- **A dynamic model capturing relevant scales is required**

Ionospheric Characterization

- **Extrapolate, interpolate, & propagate measurements to characterize varying ionosphere where there are no measurement sources**
- **Follow the ionospheric dynamics**



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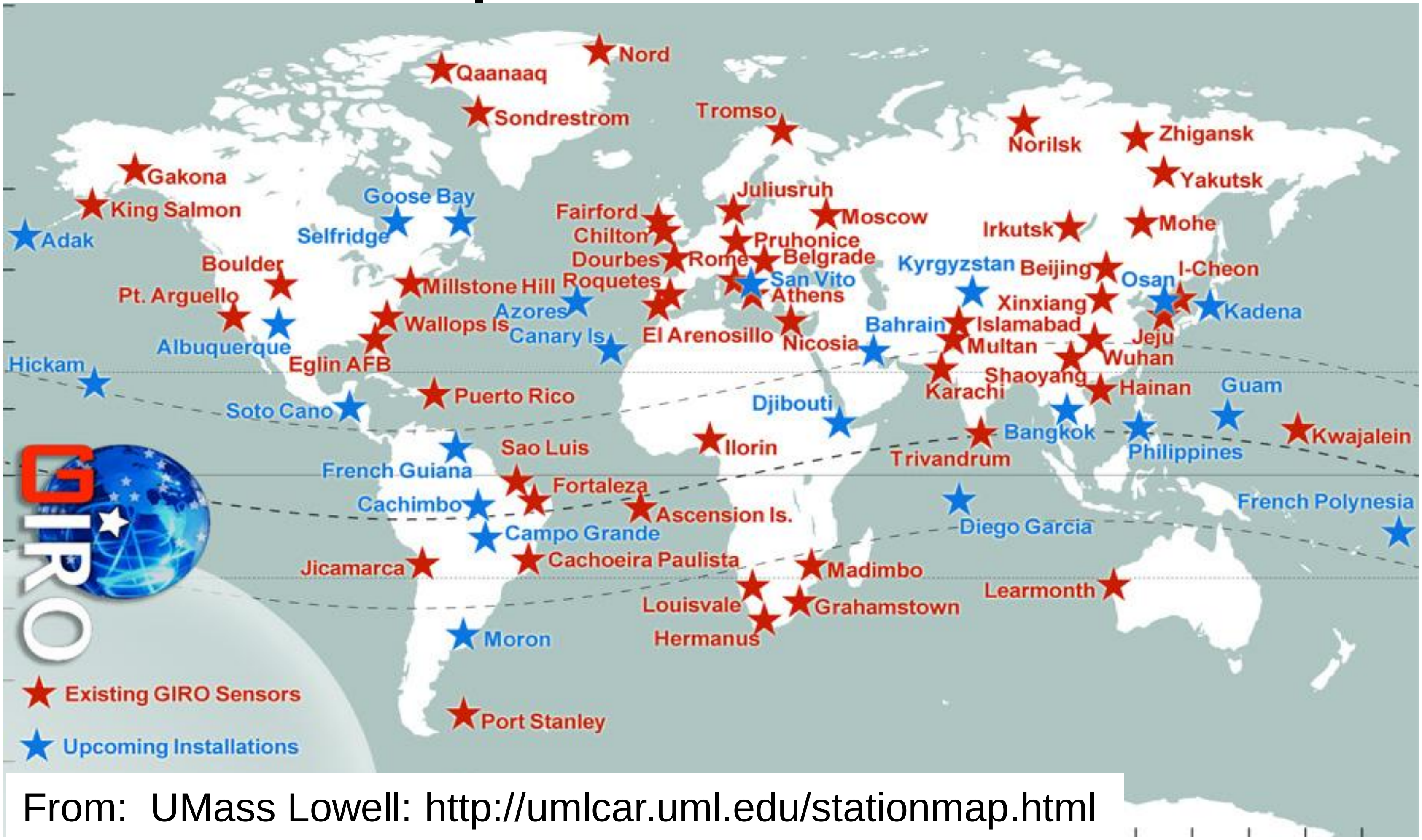
Example Raw Data Sources (1)
Ionospheric sounder network

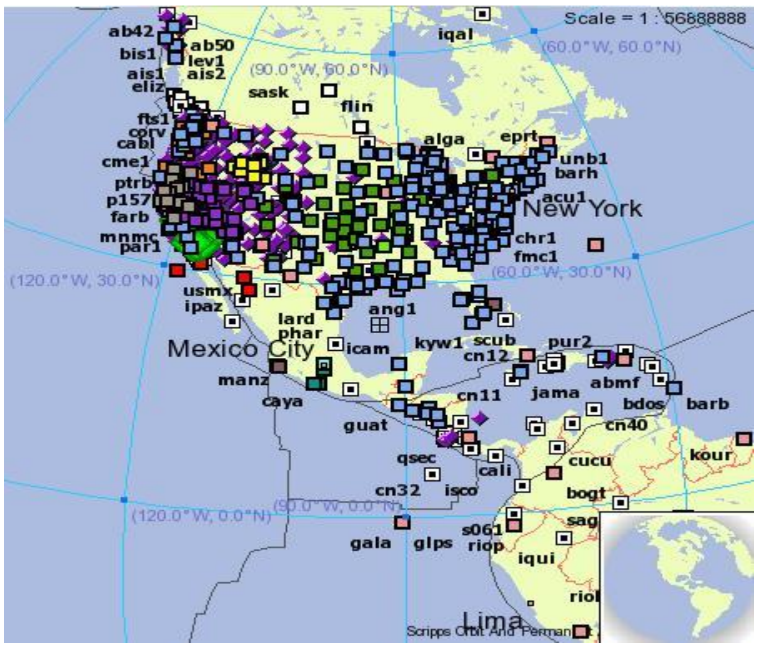


From: UMass Lowell: http://umlcar.uml.edu/stationmap.html

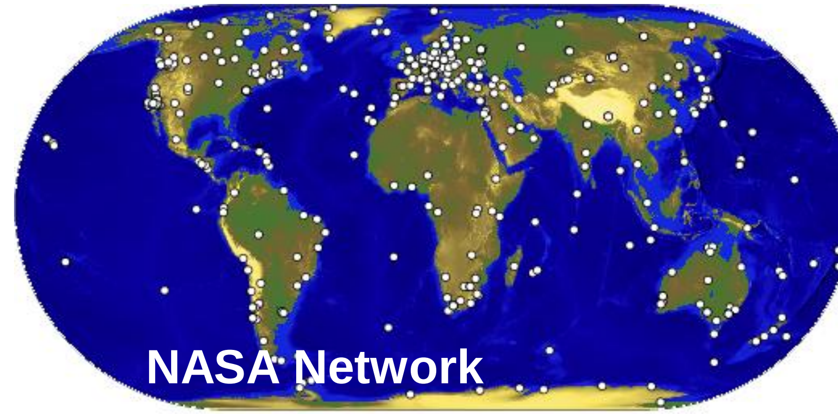
Example Raw Data sources (2)

- **Dual-frequency GPS**

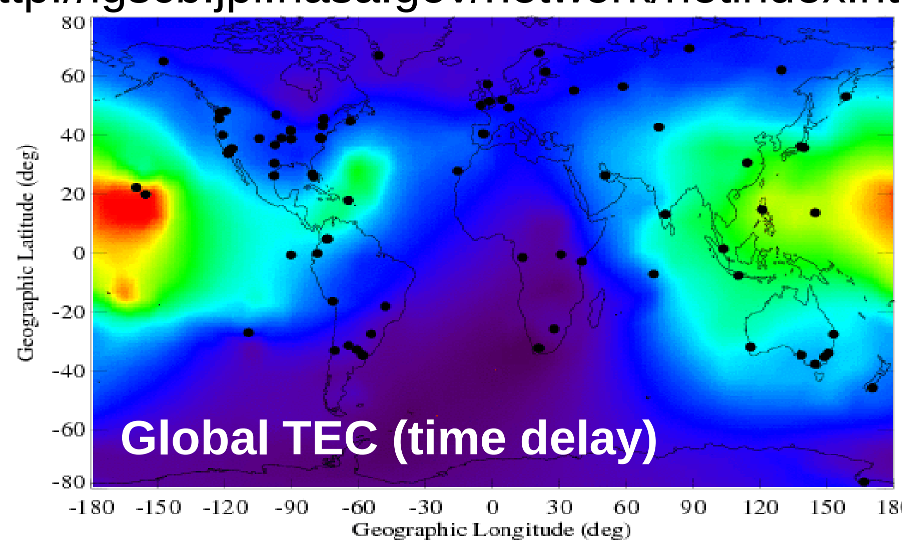
Loosely coordinated GPS Network



http://sopac.ucsd.edu/cgi-bin/somi4i

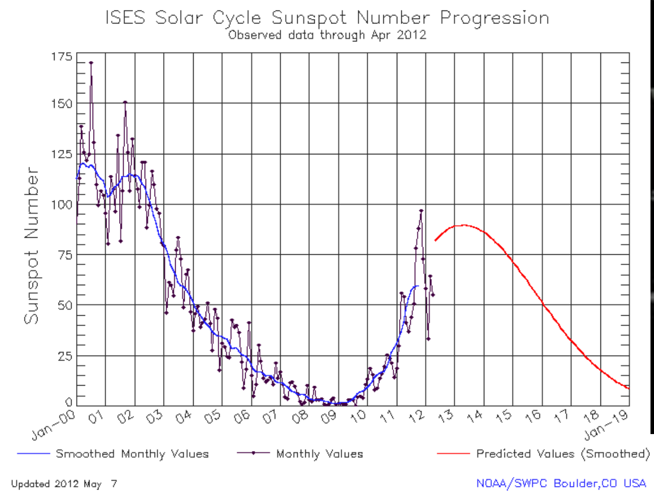


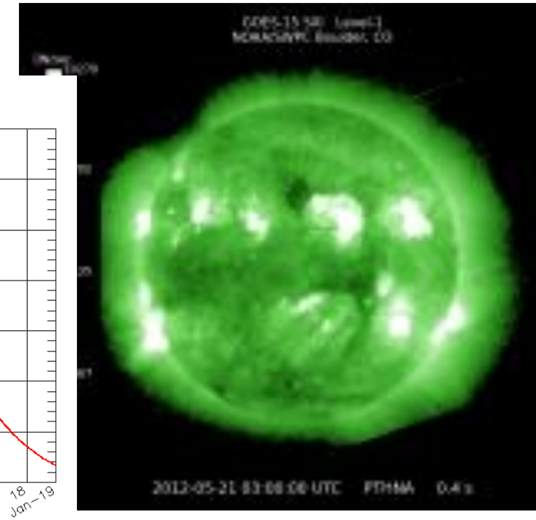
http://igscb.jpl.nasa.gov/network/netindex.html



Example Raw Data Sources (3)

Known Reference Points/ Beacons





Solar Data

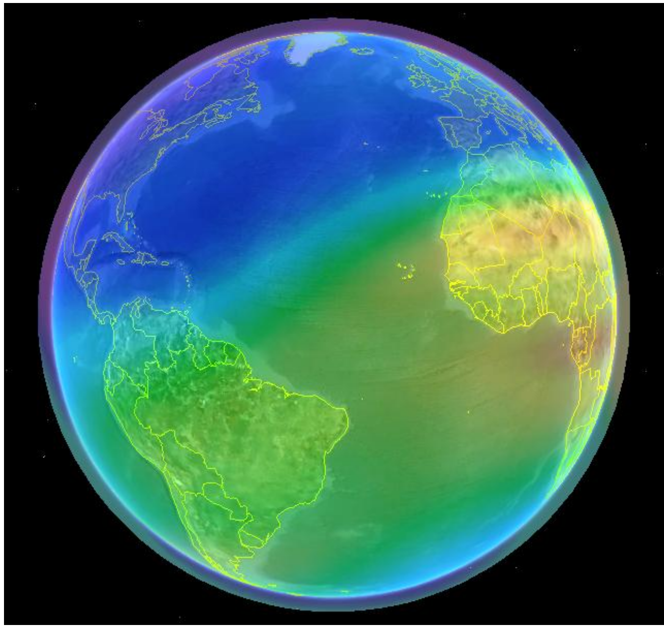
```
#
#                                 Sunspot       Stanford GOES15
#          Radio  SESC      Area          Solar  X-Ray  ------ Flares ------
#          Flux   Sunspot   10E-6   New    Mean   Bkgd    X-Ray     Optical
#  Date    10.7cm Number    Hemis.  Regions Field Flux    C  M  X  S  1  2  3
#---------------------------------------------------------------------------
2012 04 21  149    147      1630     0     -999   B5.4    3  0  0  7  1  0  0
2012 04 22  148    118      1490     1     -999   B6.4    8  0  0 10  0  0  0
2012 04 23  142    158      1580     0     -999   B5.5    3  0  0  4  0  0  0
2012 04 24  134    169      1340     3     -999   B5.1    6  0  0  5  0  0  0
2012 04 25  127    137       920     0     -999   B4.7    3  0  0  3  0  0  0
2012 04 26  119    117       540     0     -999   B4.1    2  0  0  0  0  0  0
```

Correlation and Propagation

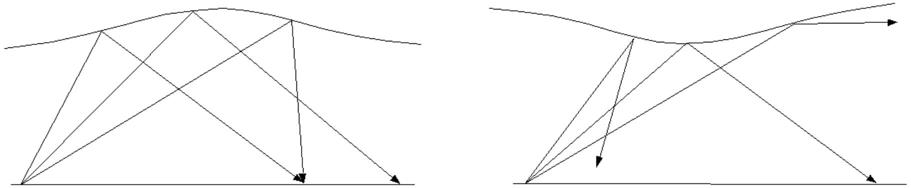
- Key to success is correlation of measurements and propagation of electron density from one location to another
- Similar to atmospheric wind, there is an ionospheric neutral wind that generally flows east-to-west in northern mid latitudes
- Traveling Ionospheric Disturbances (TIDs) propagate from their sources before dissipating
  - Auroral
  - Equatorial
  - Tropospheric coupling (Thunderstorms)
- Performers will need to incorporate these phenomena in their solutions

Phase 0 Testing

- Ionospheric physics investigation
  - Determine the temporal variation of the ionosphere
  - Determine the spatial variation & scale
  - Determine variation with frequency for geolocation
- Sensor data for Phase 1 (vector)
  - AM, single sideband, digital (PSK-31), and radar waveforms
  - Interference: local and long distance
  - Sky wave and surface wave radar intelligence data
- Vector antenna proof of concept

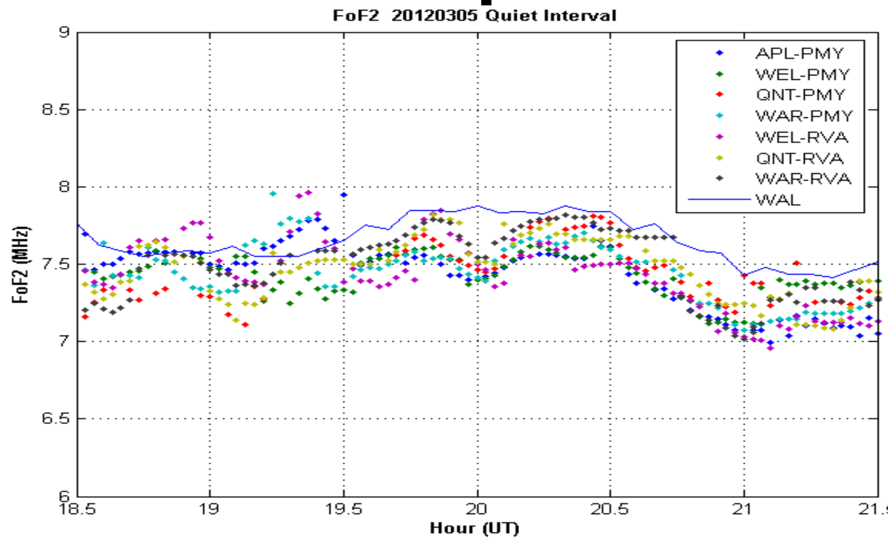


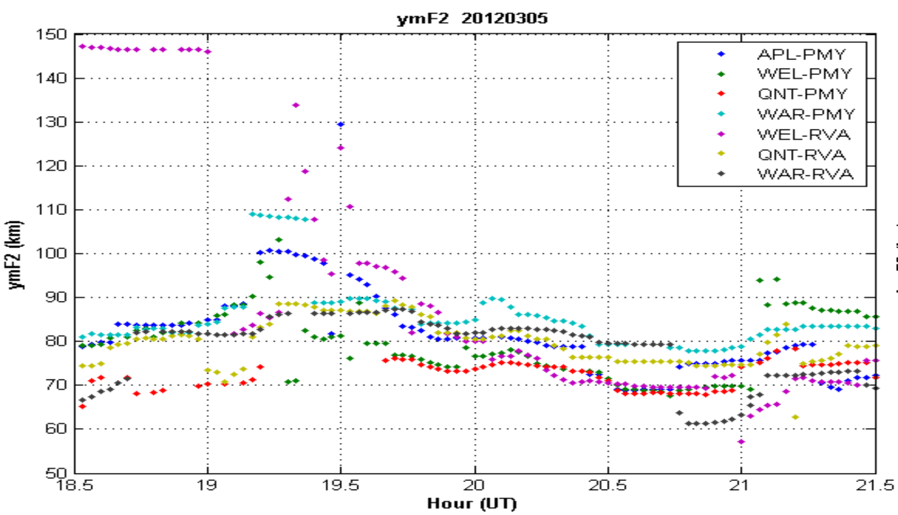
Ionospheric Electron Density Variation

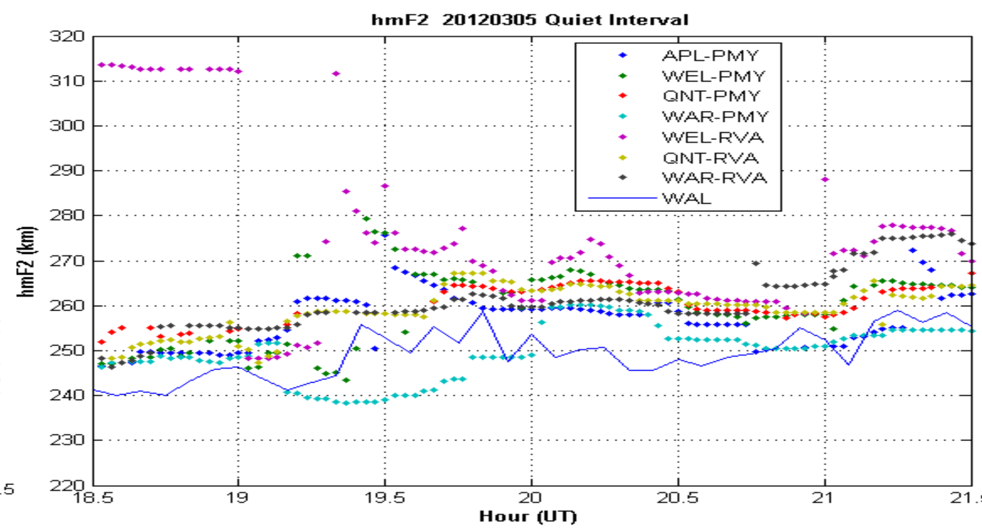


Propagation Variation

Examples


FoF2 20120305 Quiet Interval
FoF2 (MHz)
Hour (UT)
APL-PMY
WEL-PMY
QNT-PMY
WAR-PMY
WEL-RVA
QNT-RVA
WAR-RVA
WAL


ymF2 20120305
ymF2 (km)
Hour (UT)
APL-PMY
WEL-PMY
QNT-PMY
WAR-PMY
WEL-RVA
QNT-RVA
WAR-RVA


hmF2 20120305 Quiet Interval
hmF2 (km)
Hour (UT)
APL-PMY
WEL-PMY
QNT-PMY
WAR-PMY
WEL-RVA
QNT-RVA
WAR-RVA
WAL

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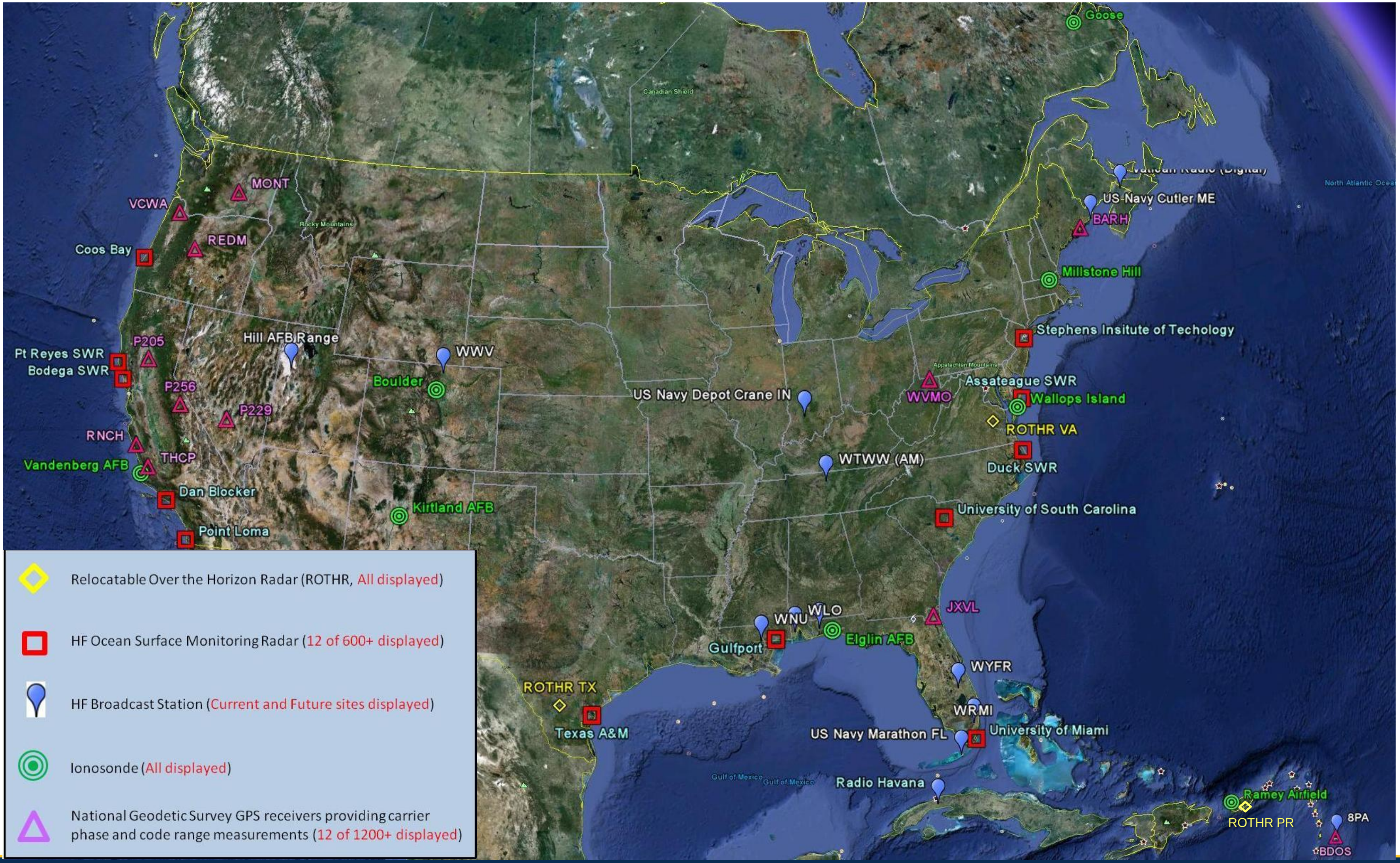
Development Concept

- Focus on CONUS and Caribbean regions
  - CONUS is simpler due to sensor density
- Utilize open and HFGeo ionospheric information sources deployed to the field and made available over the internet
- US is heavily sampled by GPS. The number of GPS sources of information will be limited

Dense Data Sources in this Region

A fraction of the potential bottom-side sources are shown



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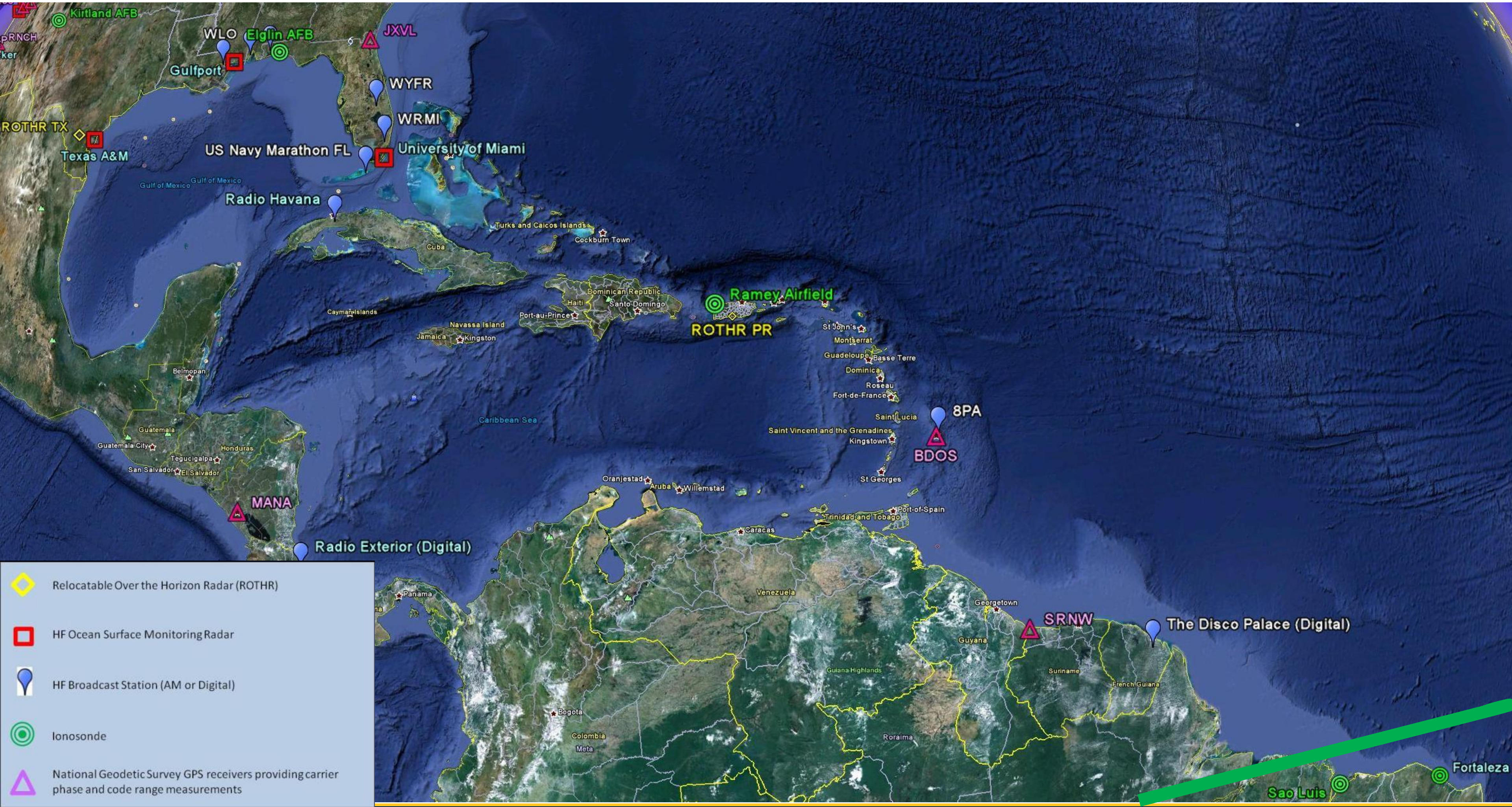
Sparse Data Locations



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What will be required to be successful?

- Data collection and interpretation / inversion
- Assimilation of multiple sources into an ionospheric model
- Dynamic updates to model
  - Interpolation
  - Extrapolation
  - Propagation
  - Performer determines update rate, but:
    - Oblique ionogram measurements are possible in as little as 30 seconds
    - 1000's of angle measurements are possible each second
- Detection of:
  - High turbulence / scintillation that makes ray path prediction inaccurate
  - Significant divergence between model and measurements
- Accurate ray tracing, inversion, and ray homing
- Incorporation of Earth digital terrain elevation data (DTED) for accurate long-range paths
- Data and model quality measures
  - Reject outlier input data
- Approach must provide persistence
  - Limited interest in single phenomena that do not provide regular updates

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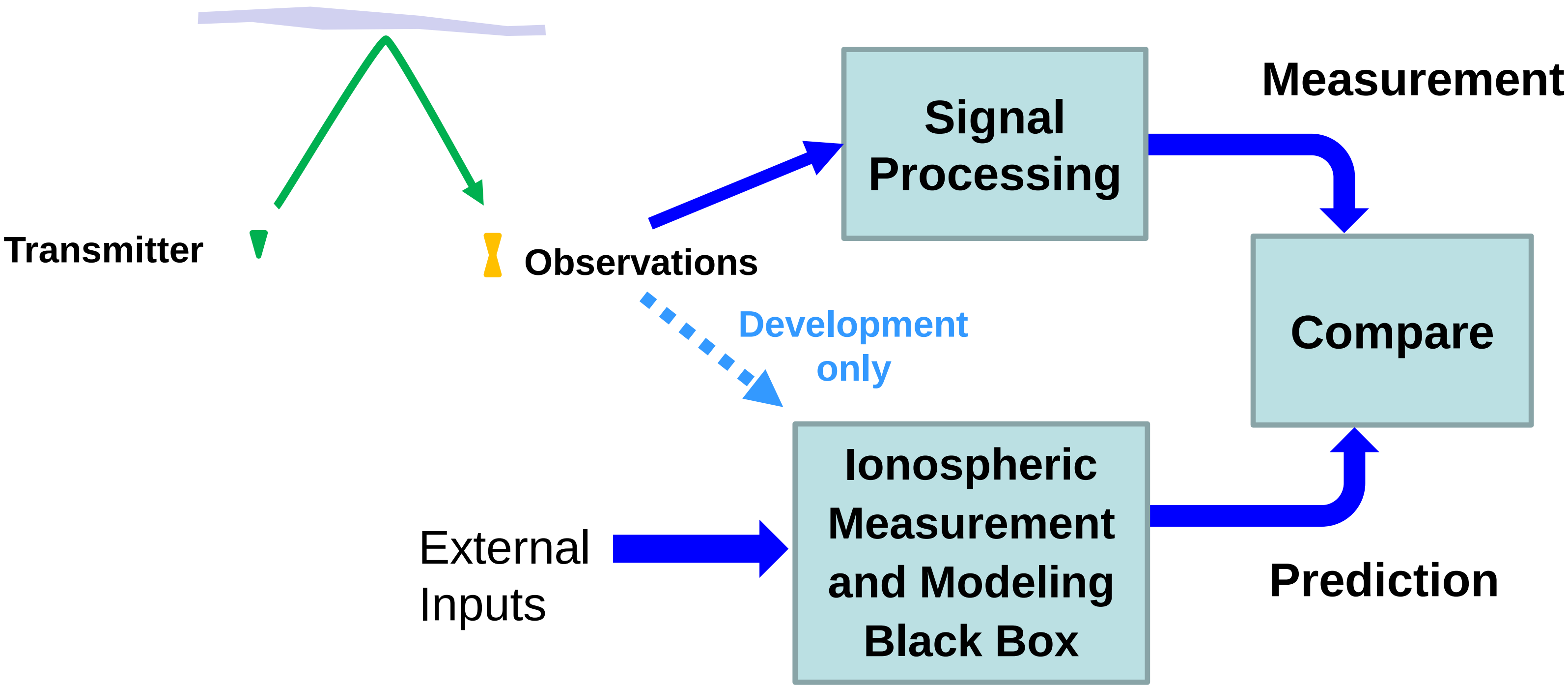
Performance Assessment



- **Performance will be determined by comparing a prediction with measurements**

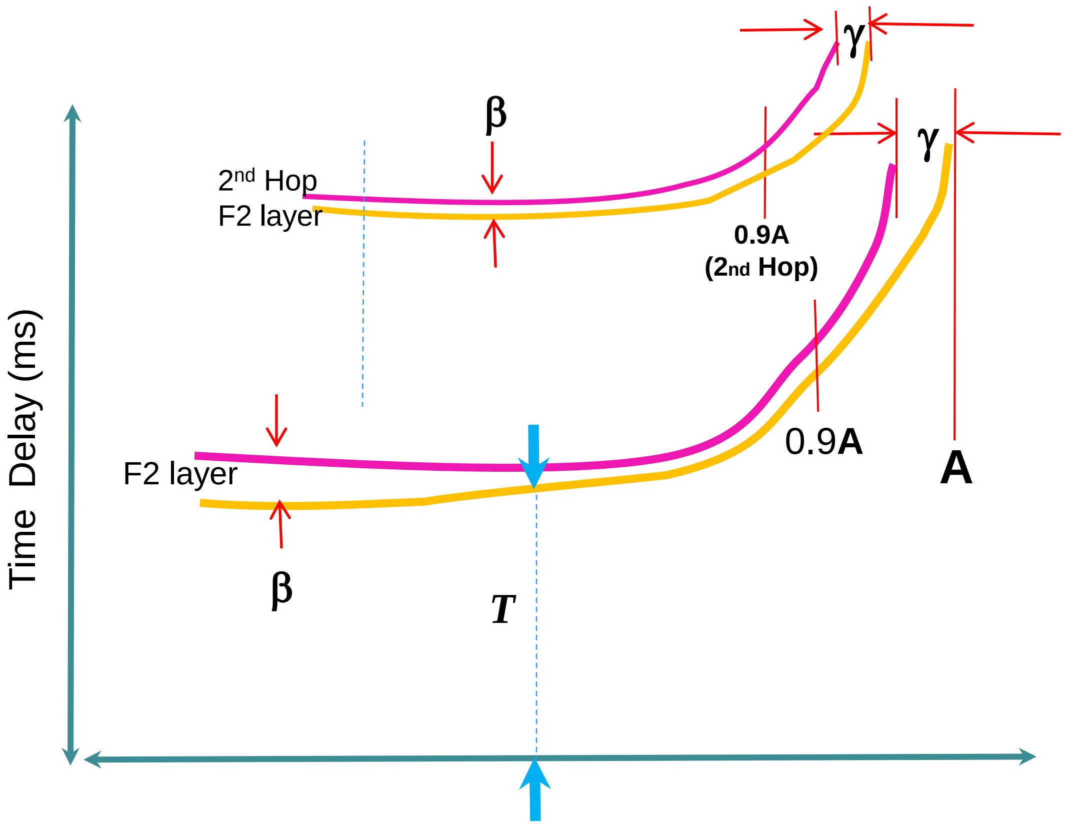
Ionospheric Technical Metrics

TBD: Pending BAA Release

Notional Test Conditions

- Day and night
- Short, medium, and long range test geometry
  - Potential test locations pairs spaced 20-50km apart to verify TID phasing
- Multiple directions relative to Earth's magnetic field to capture associated geomagnetic propagation physics
- Expect 12 test points over at least 24 hours in two campaigns (CONUS and Caribbean)
  - 3 ranges x 2 direct x 2 (day/night)
  - Channel impulse response function interleaved with ionogram measurement
  - Number of GPS sensors allowed is TBD
  - Assumed accuracy of measurement must include error budget based on sensor accuracy
- Performers to determine when the accuracy is degraded

Short Range Ionogram Metrics



A = $\mathbf{f}_{pMAX}$

γ = difference between predicted and measured f_{pMAX}

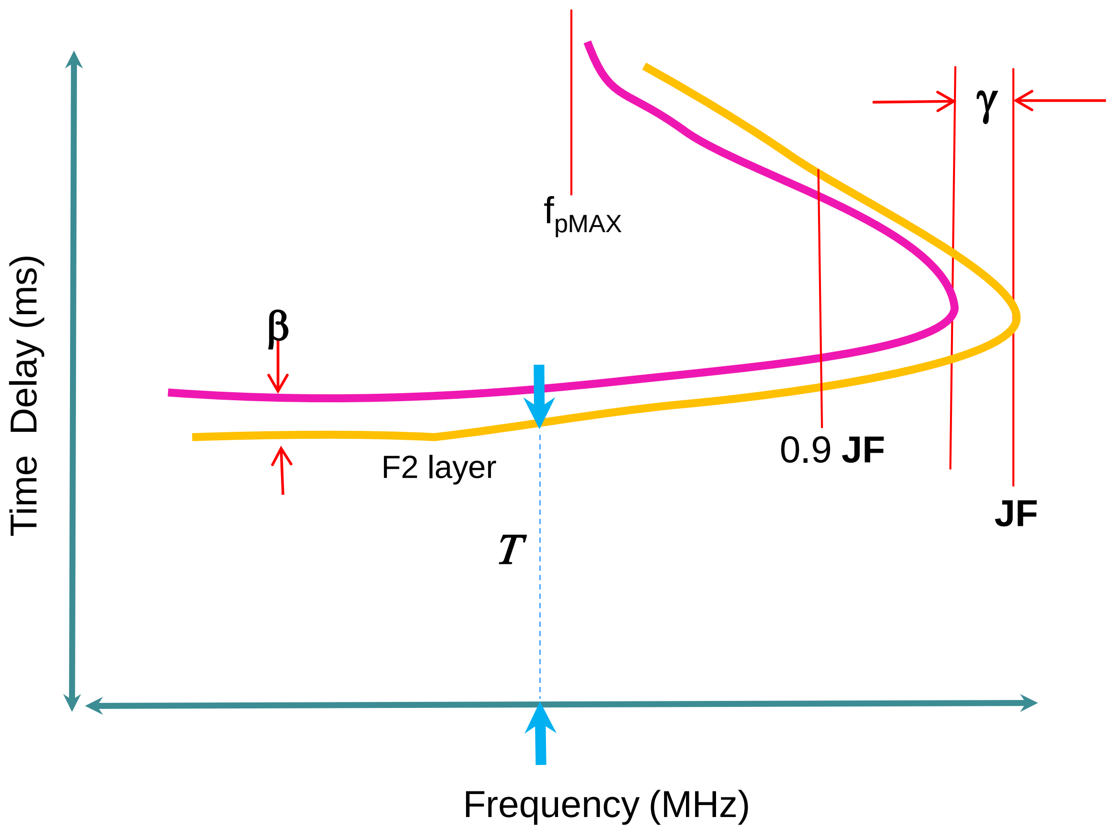
T = time delay

B = max time delta between predicted and measured ionogram

Plot is simplified to only show one and two-hop F2 O mode

Goal is to replicate ionogram with "γ" and "B" less than specified error

Medium and Long Range Ionogram Metrics



JF: Junction Frequency

γ = difference between predicted and measured JF

B = max time delta between predicted and measured ionogram

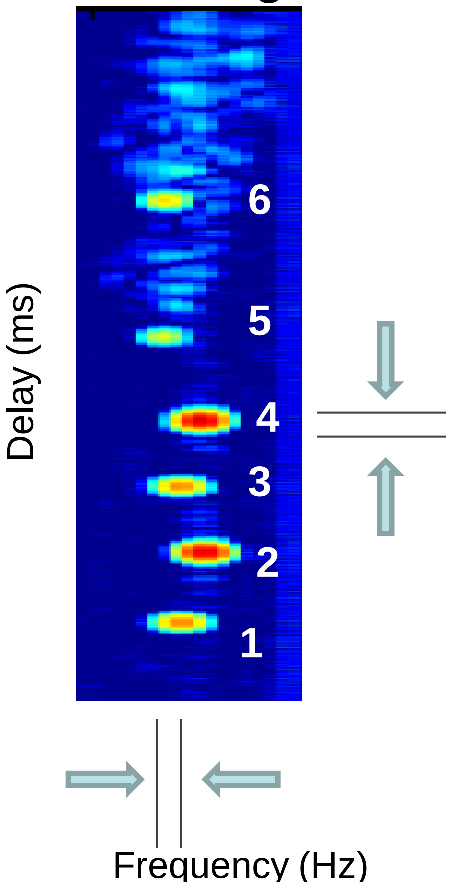
T = time delay

Typical modes: E_L, F_{1L}(o,x), F_{2L}(o,x), F_{2H}(o,x), $2F_2$,(N)F_2

For longer range paths, reproduce the instantaneous observed Junction Frequency
f_{pMax} is not typically observable

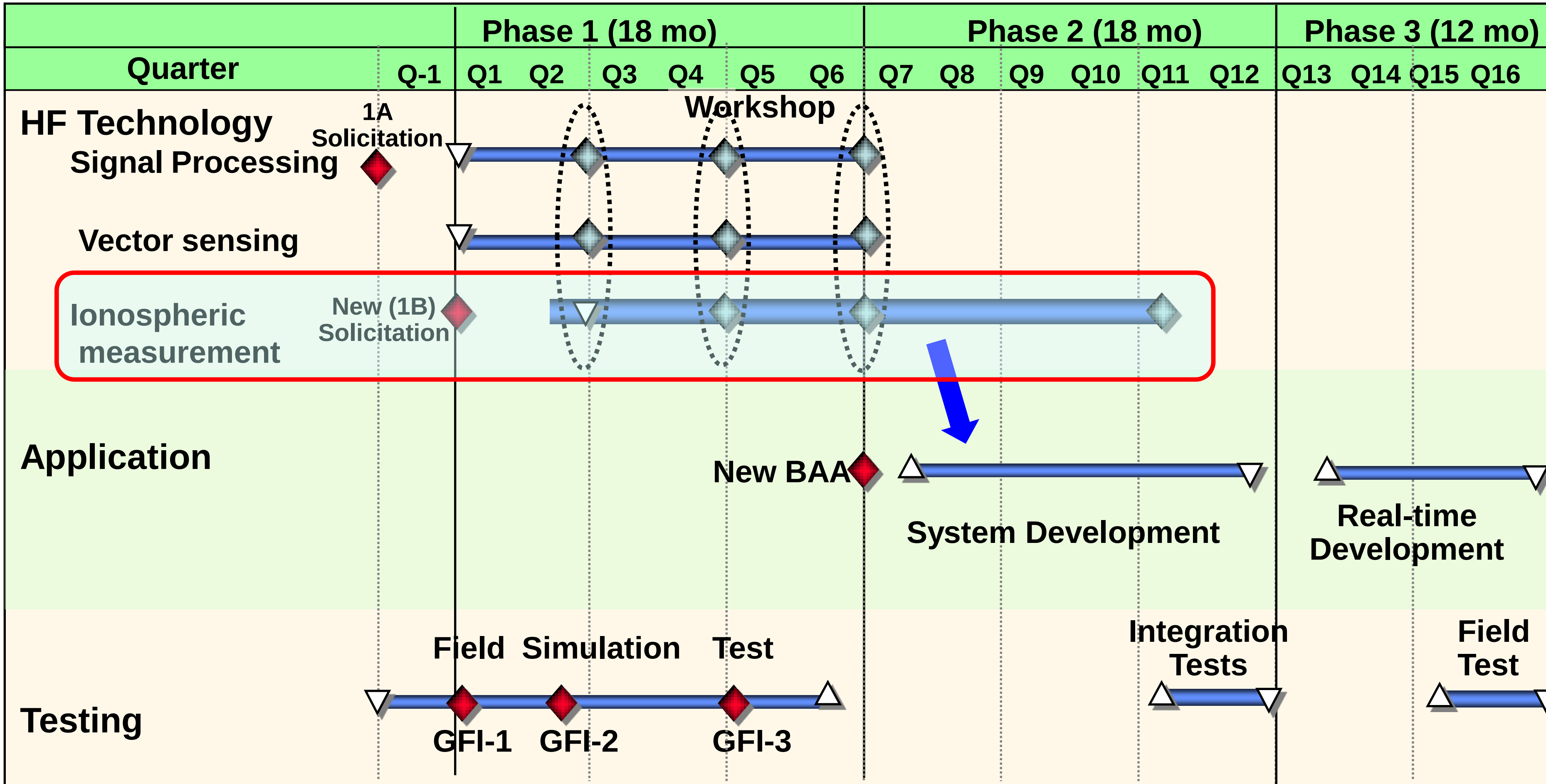
Channel Scattering Function (CSF) (a.k.a. Channel Impulse Response)

CSF Image

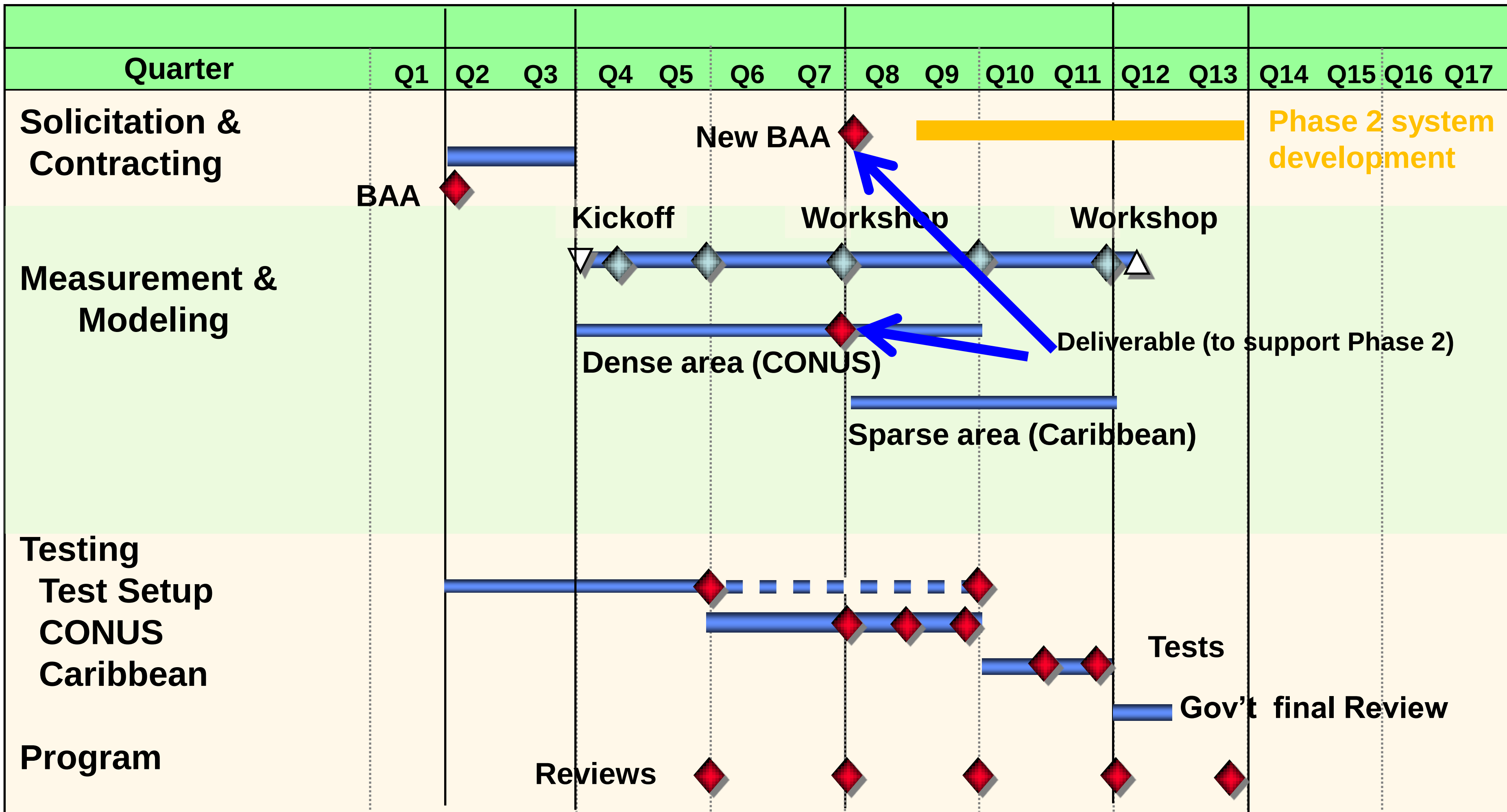


- **Predict & enumerate all major modes**
  - Delay and Doppler frequency of each mode
  - Relative amplitude (+/- 5dB)
  - Multiple bounce modes (hops)
  - Incoming and outgoing angles
  - Polarization state of each mode

HFGeo Schedule Overview



HFGeo 1B Schedule Overview



Test Equipment and Scheduling

- **Equipment purchased during HFGeo Phase 0 will be repurposed to support 1B after use in 1A**
- **Additional equipment may be deployed for the following measurements (depending upon approaches in selected proposals)**
  - **Oblique sounding**
  - **Carrier frequency/arrival angle of radio stations**
  - **Oblique reception of over-the-horizon radars**
- **HFGeo intends to make this capability available over the internet**
  - **Multi-channel receivers with scheduled measurements**
  - **Array(s) for angle-of-arrival**

Outline

- **Introduction**
- **Technical Approach**
- **Metrics and Schedule**
- **Administrative**
  - **ITAR and Security**
  - **Proposal Guidance and Evaluation Criteria**

ITAR, Security, etc.

- **There are many uses for ionospheric characterization technology**
- **The State Dept, not IARPA makes ITAR determinations**
  - **Performers need to be responsible**
- **IARPA will request pre-publication courtesy copy for review, not approval**
- **IARPA is only interested in cooperative approaches that improve understanding of the ionosphere**

Ionosphere Applications

- OTH radars
- HF communications
- ELINT
- Surveying – GPS
- Navigation – GPS
- Satellite tracking
- Power grid Impacts
- Pipelines
- FAA's WAAS
- Natural global energy transport

Eligibility Information

- **Other Government Agencies, Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), and any other similar type of organization that has a special relationship with the Government, that gives them access to privileged and/or proprietary information or access to Government equipment or real property, are not eligible to submit proposals under this BAA or participate as team members under proposals submitted by eligible entities**
- **Non-US organizations and individuals may be able to participate.**
  - **Must comply with Non-Disclosure Agreements, Security Regulations, Export Control Laws, etc. as appropriate**
  - **Specific guidance for non-US participation will be provided in the BAA**

Proposal Guidance

- **Your proposal should include a full discussion of the technical approach that will be used to meet the program goals.**

- **Programmatic issues to be addressed in the proposal:**
  - **Your team's current technical capabilities.**
  - **Key resources needed (not currently available to your team), to include capital equipment and special expertise. The risk in acquiring these key resources, and mitigation strategies, should be indicated as well.**
  - **A teaming plan along with the roles and responsibilities of each member of the research team.**
  - **End of phase and some intermediate milestones are set, but it is expected that other intermediate milestones that are on the critical path of the proposed approach will be offered.**
  - **A schedule of all milestones including a clearly charted description of the various risk mitigation strategies that will be undertaken to achieve program goals.**

Proposal Evaluation Criteria

- Overall Scientific and Technical Merit
- Effectiveness of Proposed Work Plan
- Relevance to IARPA Mission and HFGeo Program Goals
- Relevant Experience and Expertise
- Cost Realism

Evaluation criteria will appear in the BAA.

Additional Information

- Email dni-iarpa-baa-12-04@ugov.gov with additional questions
- HFGeo BAA will be posted on FedBizOpps website (www.fedbizopps.gov) and then noted on www.iarpa.gov
- Q&As will appear after the BAA is posted. See http://www.iarpa.gov/solicitations_hfgeo.html

Conclusion

- HFGeo will develop technology for the next generation of HF intelligence sensors
- The ionosphere is an integral part of the sensor systems
- More accurate ionospheric information is needed to increase accuracy
- This phase of the HFGeo Program will develop the technology to provide more accurate ionospheric information