Raytracing Models

Signal propagation modeling using RayTRIX and RTAM

Ivan Galkin[1], Bodo Reinisch[1,2], Xueqin Huang, Chris Granz[2], Ryan Hamel[2], Dieter Bilitza[3,4]

(1) Space Science Laboratory, UMass Lowell, USA
(2) Lowell Digisonde International, LLC, Lowell, MA 01854, USA
(3) Department of Physics and Astronomy, George Mason Universty, Fairfax, VA, USA
(4) Space Physics Data Facility, NASA, GSFC, Greenbelt, MD 20771, USA

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Outline

- Background: HF
- HF signal propagation modeling
  - Raytracing is only one approach to the task
  - Two scenarios for raytracing
  - Multi-path propagation
  - D-region impact on signal strength
- Different solutions for managing HF
  - Climate specs: IRI
  - Measurements: ionosondes where available, GNSS: TEC and RO
  - Weather models: IRTAM-based systems with raytracing
- RayTRIX CQP
  - Computation speed up: Quasi-parabolic profile
  - GPU solution for a 5 sec oblique ionogram computation
- Path forward
  - IRTAM enhancements for a better weather monitoring
  - Sensing D region with ionosondes

Historical Reference: High Frequency

skywave

1901

Marconi

1920

Appleton

First ionosondes

1925

The world goes wireless, most extraordinarily

1930s

WW2
radar era

IGY
150 ionosondes
1956-1957

1970s
peak of interest in ionospheric radio

The world goes into space, most extraordinarily

ISR era

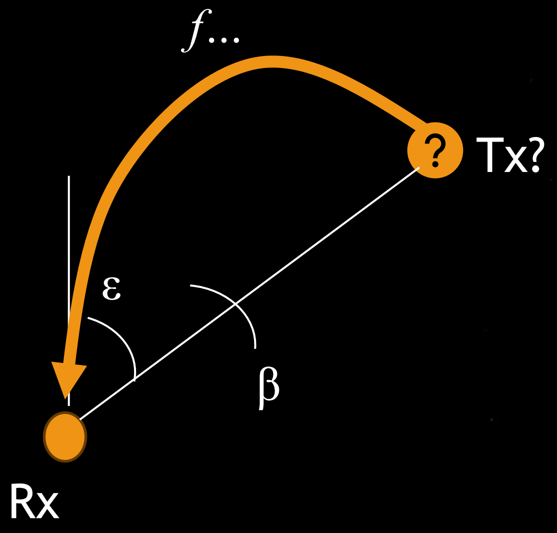
GPS era
with tomography

RO era

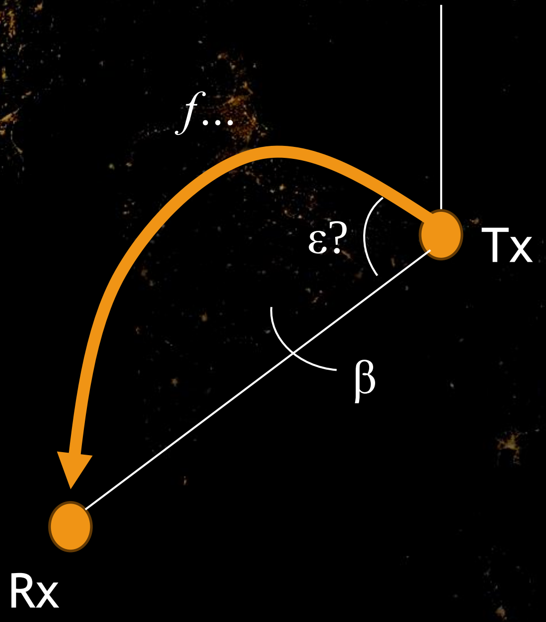
TID era

HF Dead
declarations

Who cares? Three scenarios of HF signal modeling

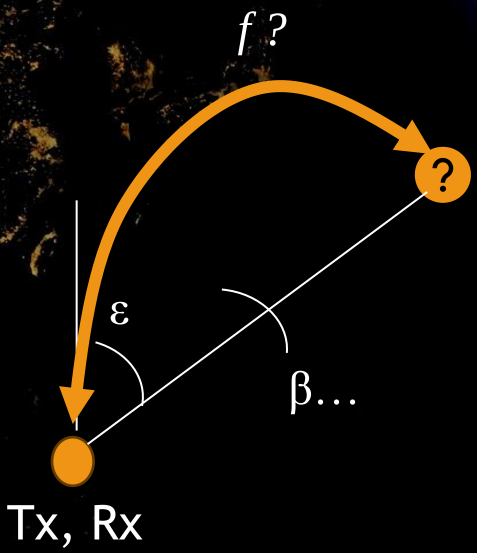


GEOLOCATION
of uncooperative transmitters



FREQUENCY MANAGEMENT
of HF communications

Ray homing is involved

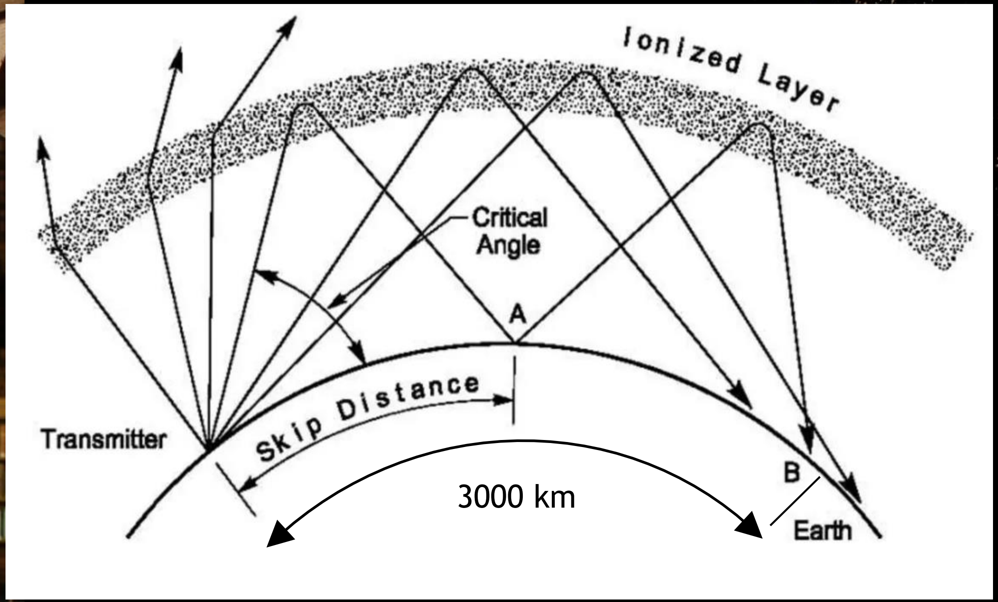


OVER THE HORIZON RADAR
searching reflecting targets
also in backscatter mode

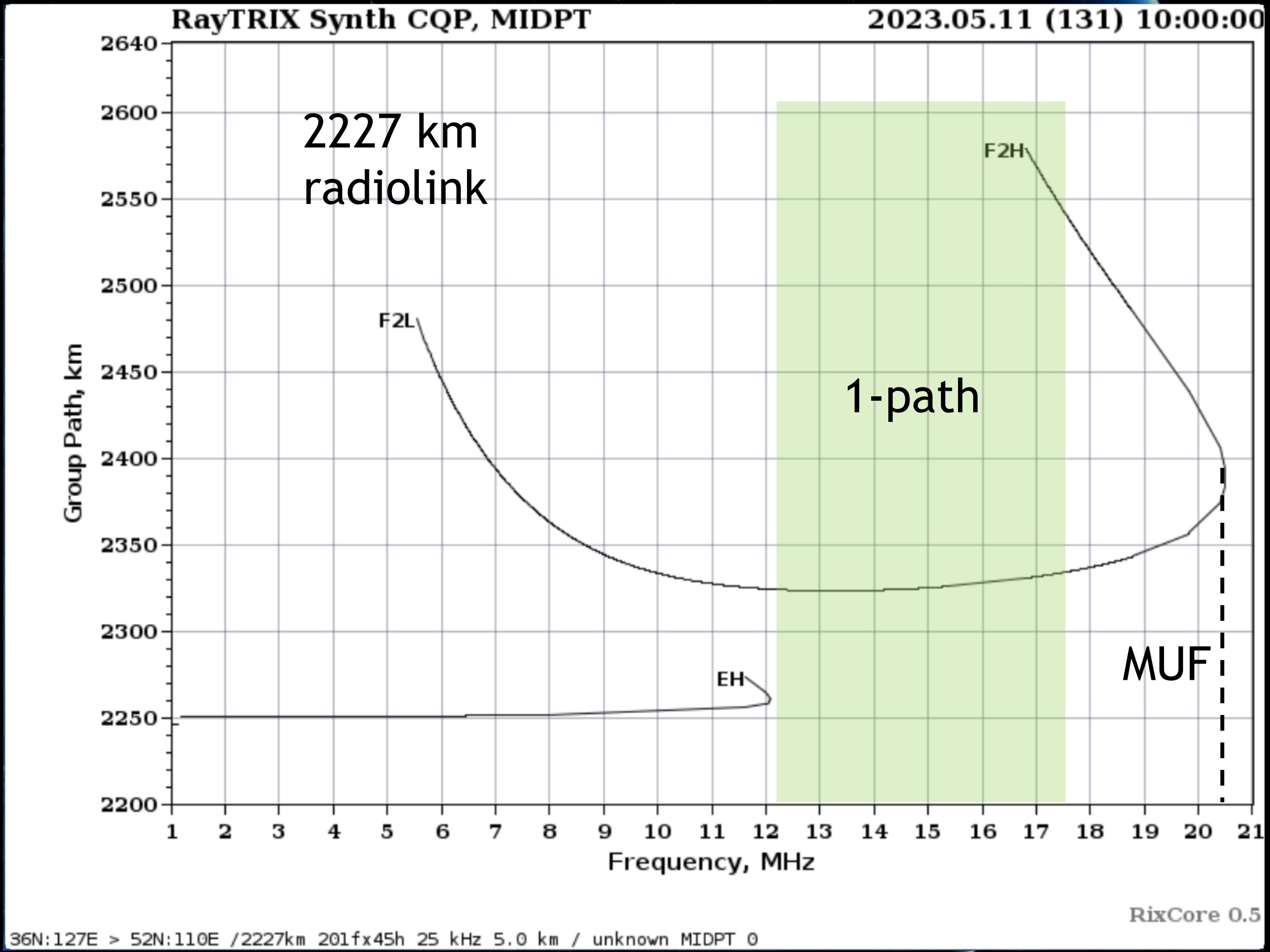
Frequency management for ICAO

- HF is used for safety messaging
- HF is used as backup voice comms to VHF/SAT
- ICAO: HF radio links of tremendous variety

HF Comms: need for frequency management



MUF(3000) = maximum frequency that can be used for communications over 3000 km distance via ionosphere

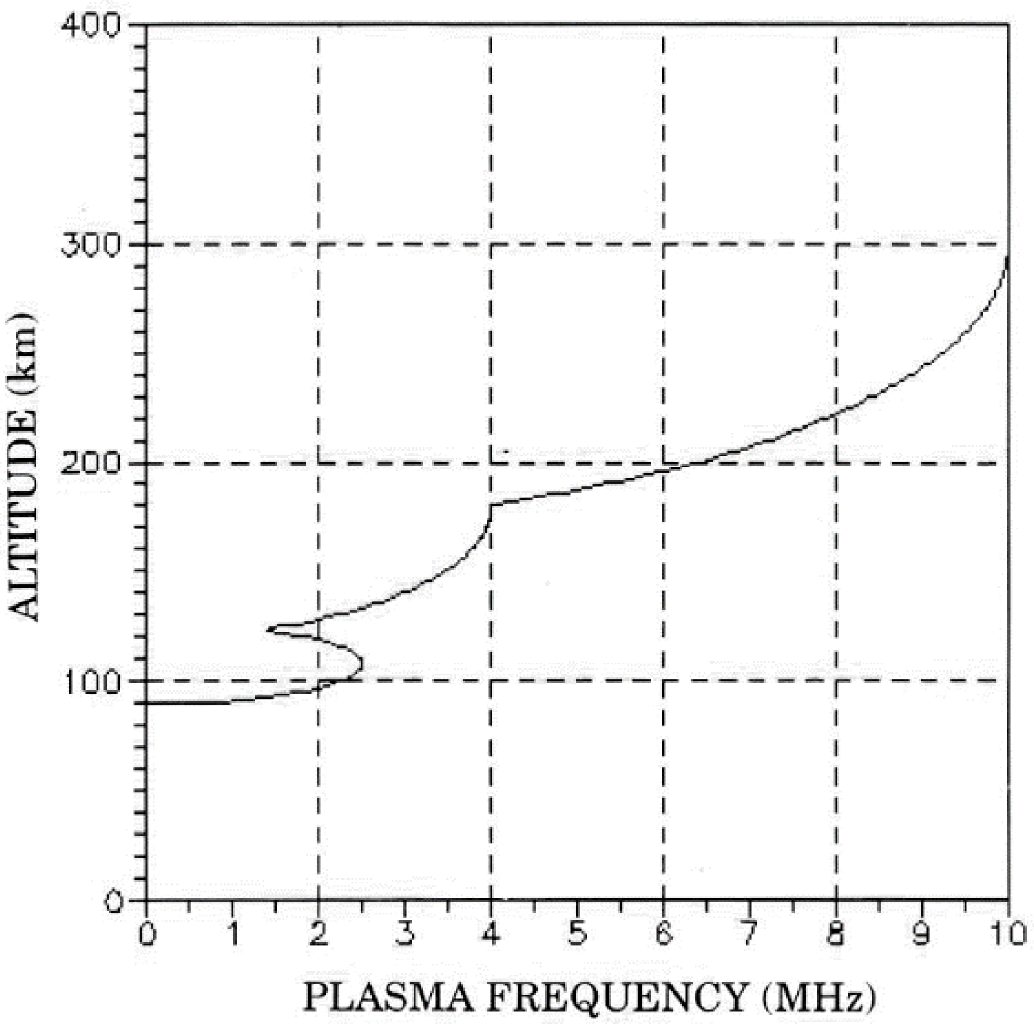


OBLIQUE IONOGRAM SYNTHESIZER

Source of MUF Information, climate and weather

TECHNIQUE	APPLICATION	RATING
1. IRI quiet-time prediction: M(3000)	Multitude of users	Great at systems R&D
2. Ionosonde: Local Weather foF2	HF Enthusiasts	Good for NmF2, but only local
3. Ionosonde: MUF computation for specific D	HF Enthusiasts	Nice, but only near an ionosonde (local)
4. Global: Negative storm detection from foF2 or VTEC timelines	PECASUS	Good start
5. Percent ΔMUF(3000) "anomaly" maps	PECASUS	Good
6. Ray-tracing through CQP ionosphere nowcast	Specific radio link evaluation	Second Best: a few seconds on a GPU
7. Ray-tracing through realistic ionosphere nowcast	Accurate evaluation of specific radio links	Best, but unrealistic for real-time applications

Use parabolas for Ne profile descroption



$$f^2(r) = \frac{a}{r^2} + \frac{b}{r} + c \qquad \text{(parabolic)}$$

f - plasma frequency, MHz

r - distance from the Earth's center, km

a, b, c - model parameters

$$f^2(r) = f_m^2 \left\{ 1 - \left(\frac{r - r_m}{y} \right)^2 \right\} \qquad \text{(parabolic)}$$

f_m - peak plasma frequency

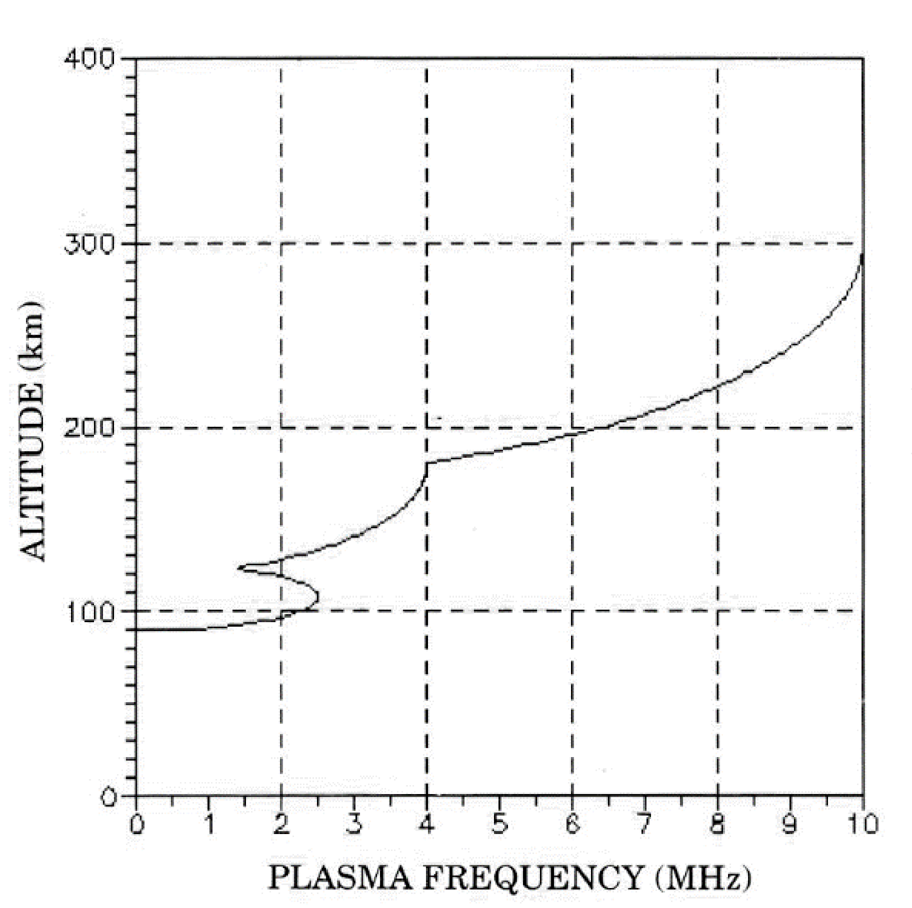
r_m - radial distance for the peak

y - thickness of the layer

$$f^2(r) = f_m^2 \left\{ 1 - \left(\frac{r - r_m}{y} \right)^2 \left(\frac{r_b}{r} \right)^2 \right\} \qquad \text{(quasi-parabolic)}$$

r_b - radial distance for the bottom of the layer

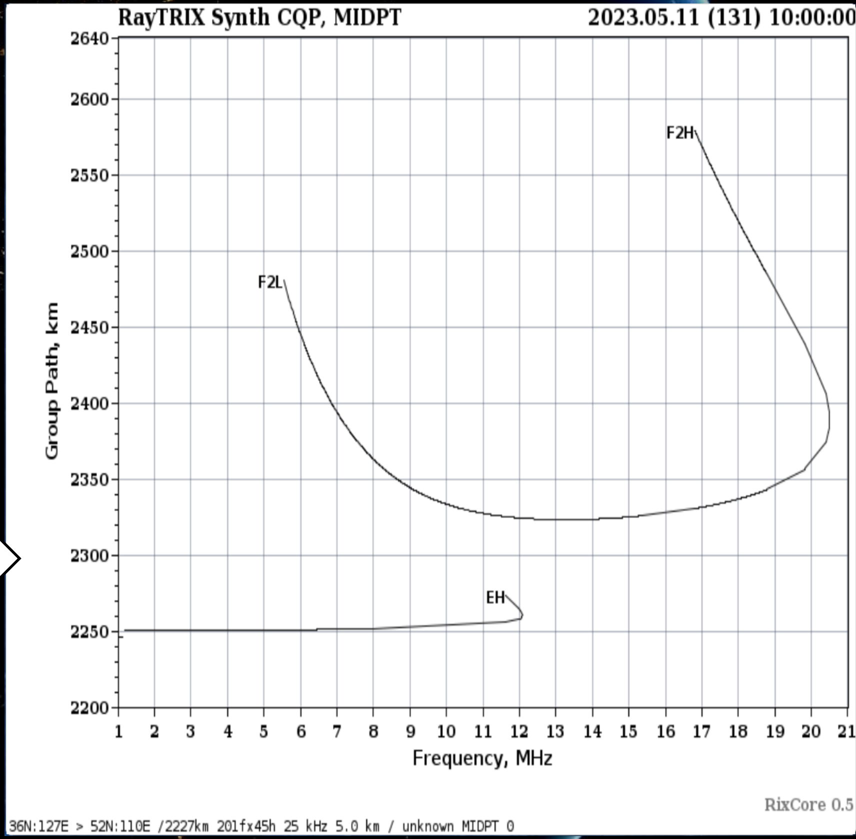
CQP: Composite Quasi-Parabolic



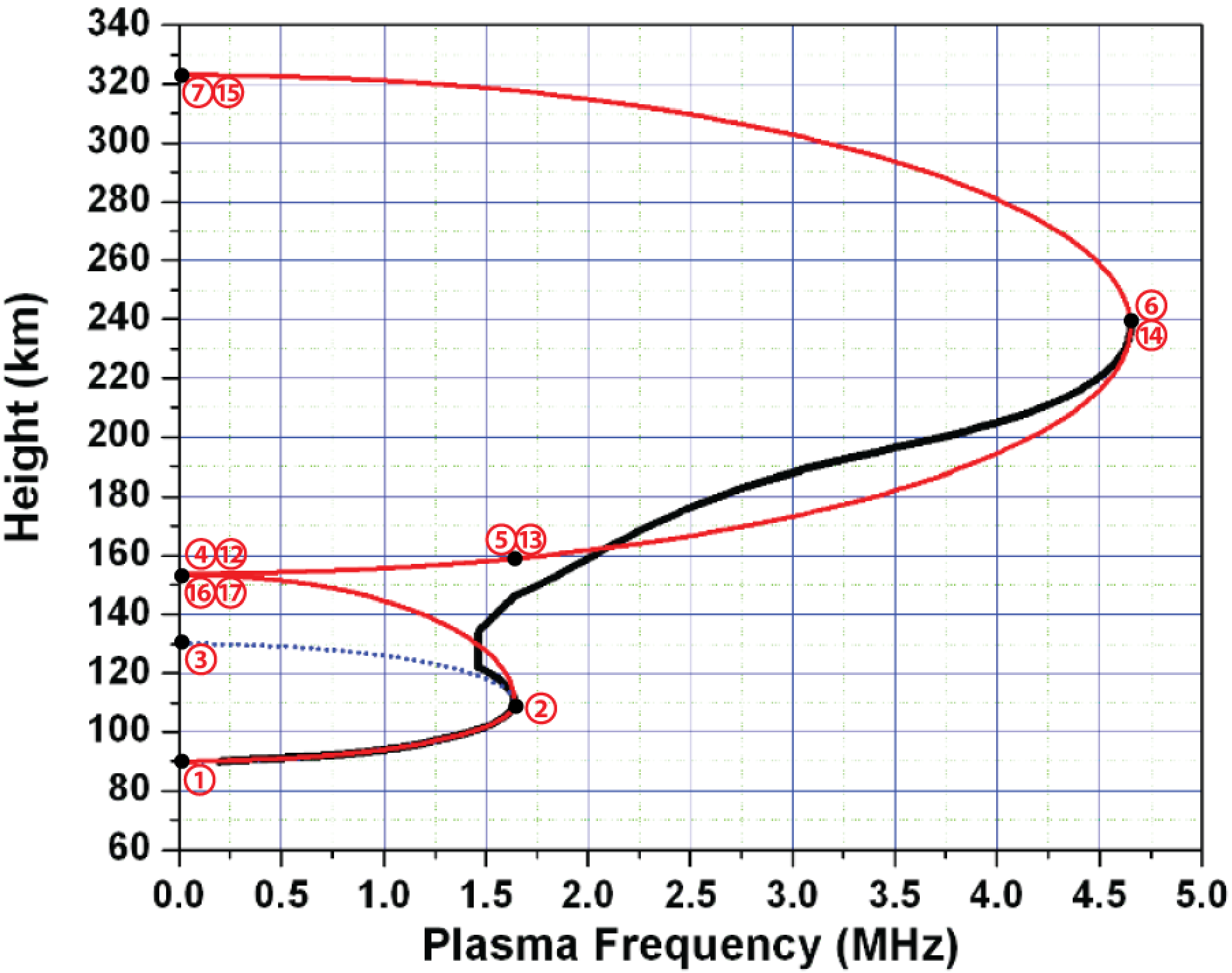
- CQP allows analytical solution to one ray
  - Given CQP profile at mid-point between Tx and Rx
  - Given particular frequency and launch angle
  - Get ray arrival location analytically
    - Meaning, no differential equations to solve
- Homing is still required

Concept for IRI-based Frequency Management

- Start: IRI climate
- Assimilation of ionosonde data = IRTAM
  - Real-time is possible
- For the given radio path with Tx and Rx coordinates
  - Use IRTAM to obtain 1D vertical density profile at mid-point of the link
  - Fit several quasi-parabolic segments to the IRTAM profile
    - Composite Quasi-Parabolic Representation = CQP
  - Run raytracing computation for each segment
    - Step frequencies until no more signal
  - Compute MUF for each segment
  - Compute the freq.band of the least multi-path
- Advantages over MUF(3000)..
  - Individual MUF and best frequency band for radio links of specific geometry (ground distance, Tx and Rx)
  - Ionospheric specification made at the relevant points of the channel



Fitting CQP to IRTAM profile: 3-layer algorithm



E-Layer: ①=$(r_{bE},0)$, ②=(r_{mE},f_{mE}), ③=$(r_{TE},0)$.

F1-Layer: ④=$(r_{bF1},0)$, ⑤=(r_{SF1},f_{SF1}), ⑥=(r_{mF1},f_{mF1}), ⑦=$(r_{TF1},0)$.

F2-Layer: ⑧=$(r_{bF2},0)$, ⑨=(r_{SF2},f_{SF2}), ⑩ =(r_{mF2},f_{mF2}), ⑪ =$(r_{TF2},0)$.

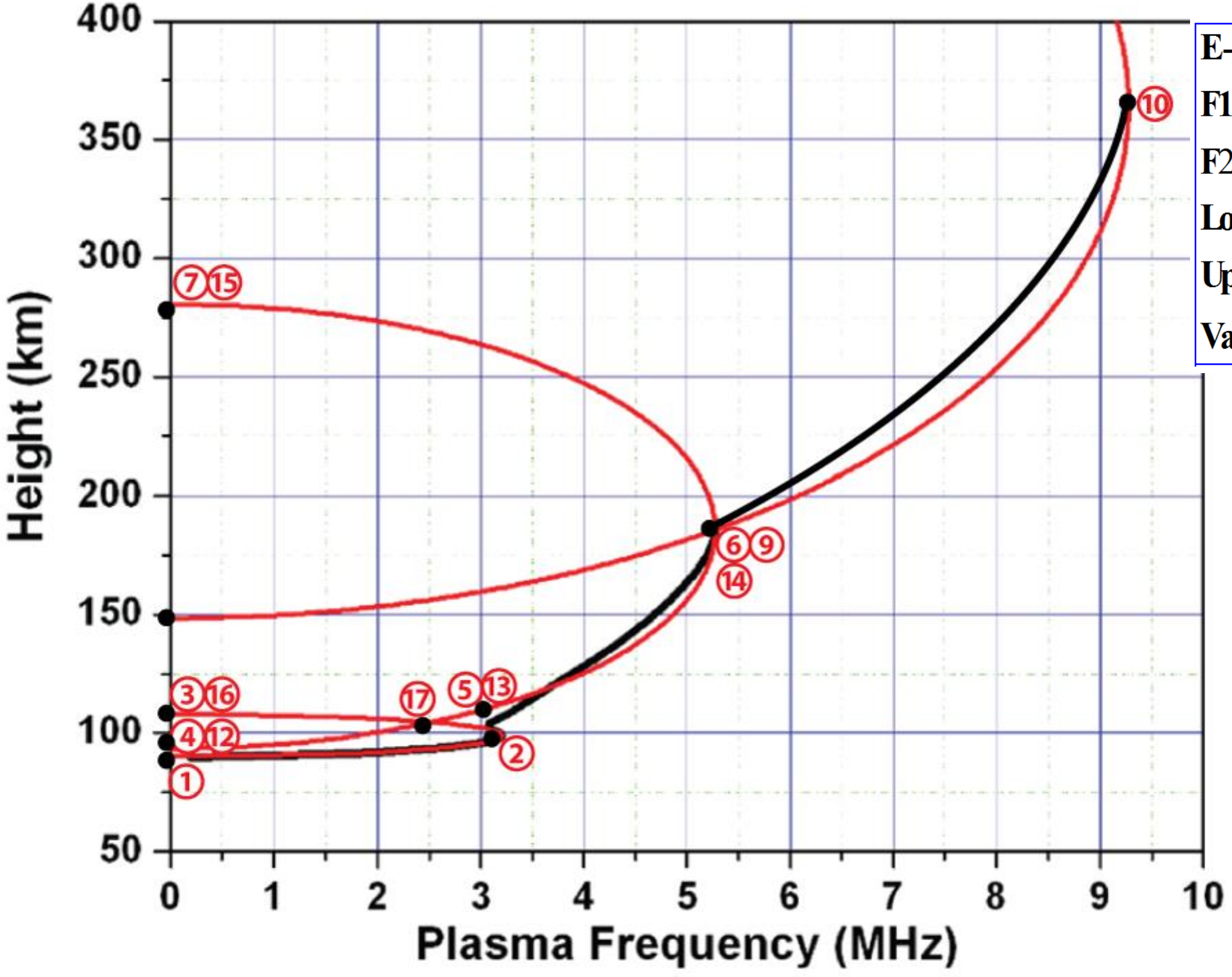
Lowest-F-Layer: ⑫ =$(r_{bF},0)$, ⑬ =(r_{SF},f_{SF}), ⑭ =(r_{mF},f_{mF}), ⑮ =$(r_{TF},0)$.

Upper-E-Layer (Valley-Lower-part): ⑯ =$(r_{T,Upper\text{-}E},0)$.

Valley-bottom: ⑰ =(r_{VB},f_{VB}).

- Analytical solutions exist for given QP
  - For any given operating frequency *f*, the *D*(β) chart of distance *D* as function of elevation angle *β* is computed
- For a given distance D_{tr}, **homing procedure** attempts to finds *β* from the chart whose *D* matches D_{tr}

Fitting CQP to IRTAM profile: 3-layer algorithm



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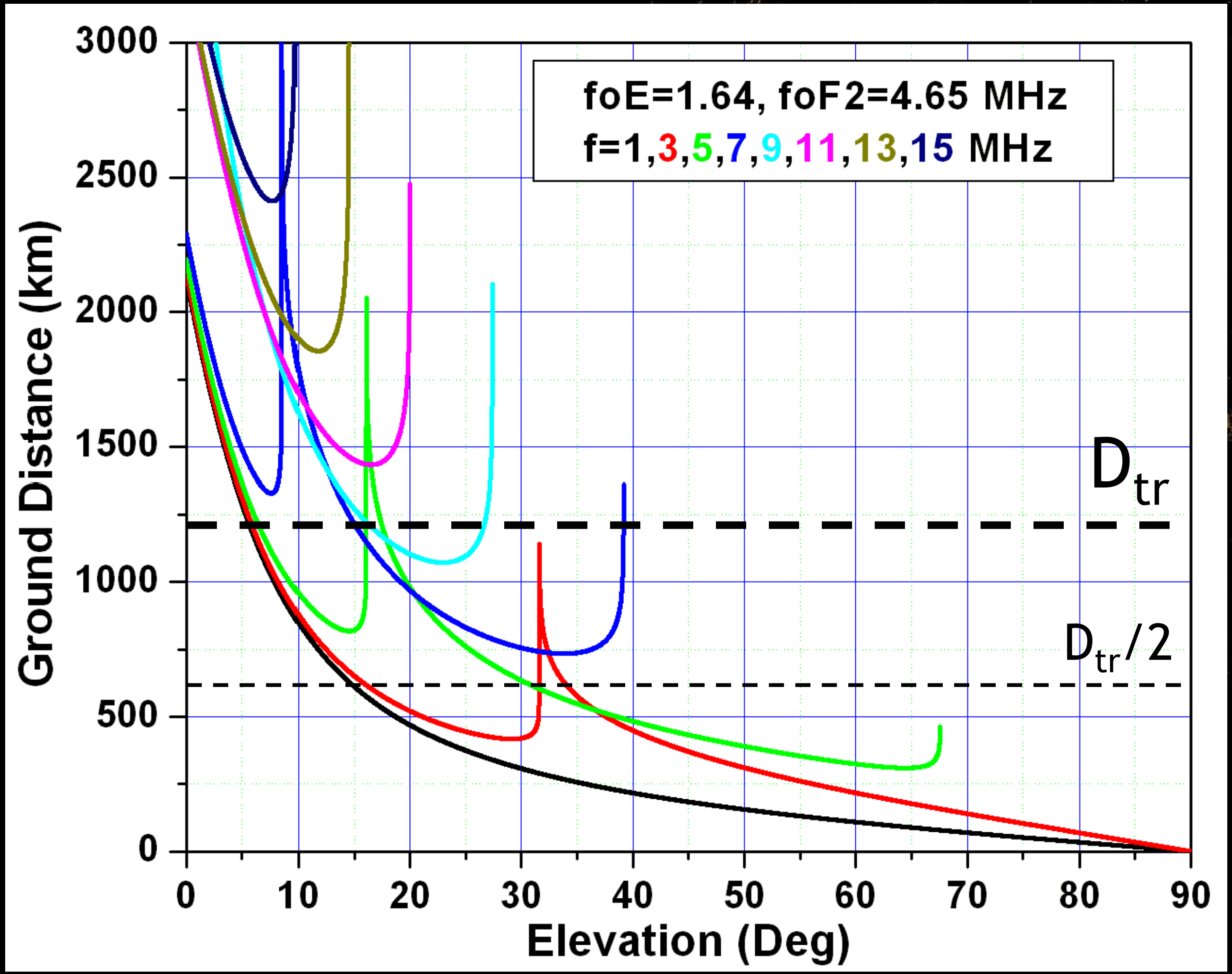
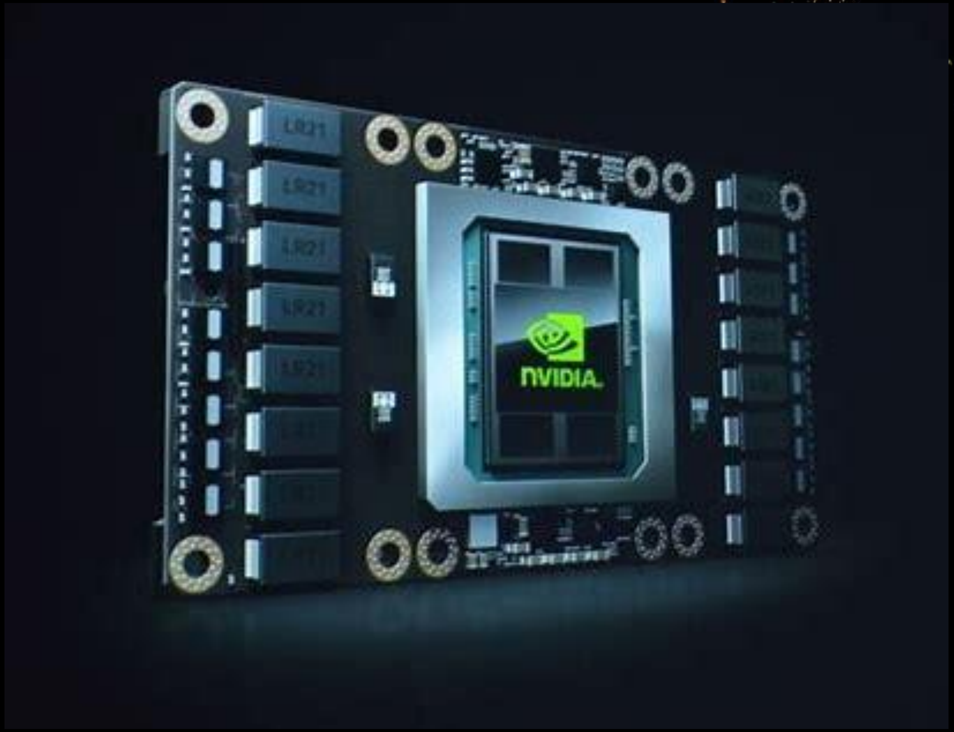
Homing is still involved



- QP representation allows analytical solution
  - That allows the speedup
  - No need to ray-trace piecewise
- Still need to find the elevation angle β that has matching D
- This is *homing* procedure
- Uses binary search method

GPU Implementation



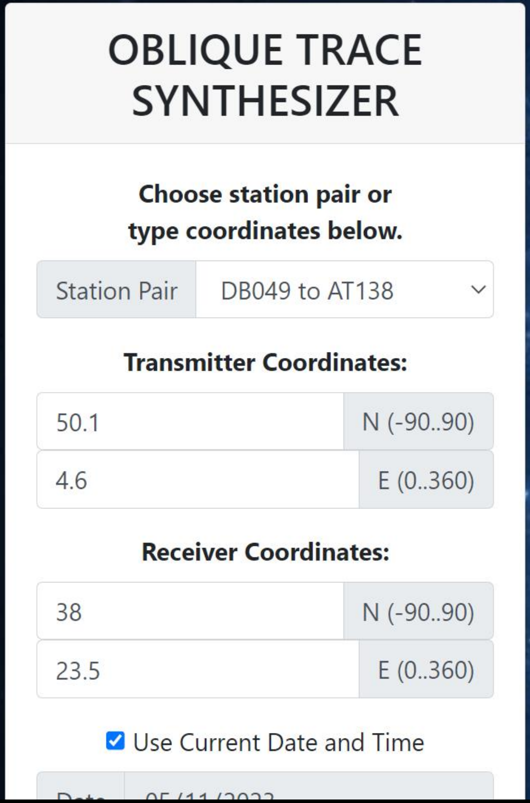
- Running time to synthesize one ionogram is about 5 seconds
- After testing CUDA, migrated to OpenCL, then migrated to OpenGL and finally to C++
- ToDo: 2-hop computation

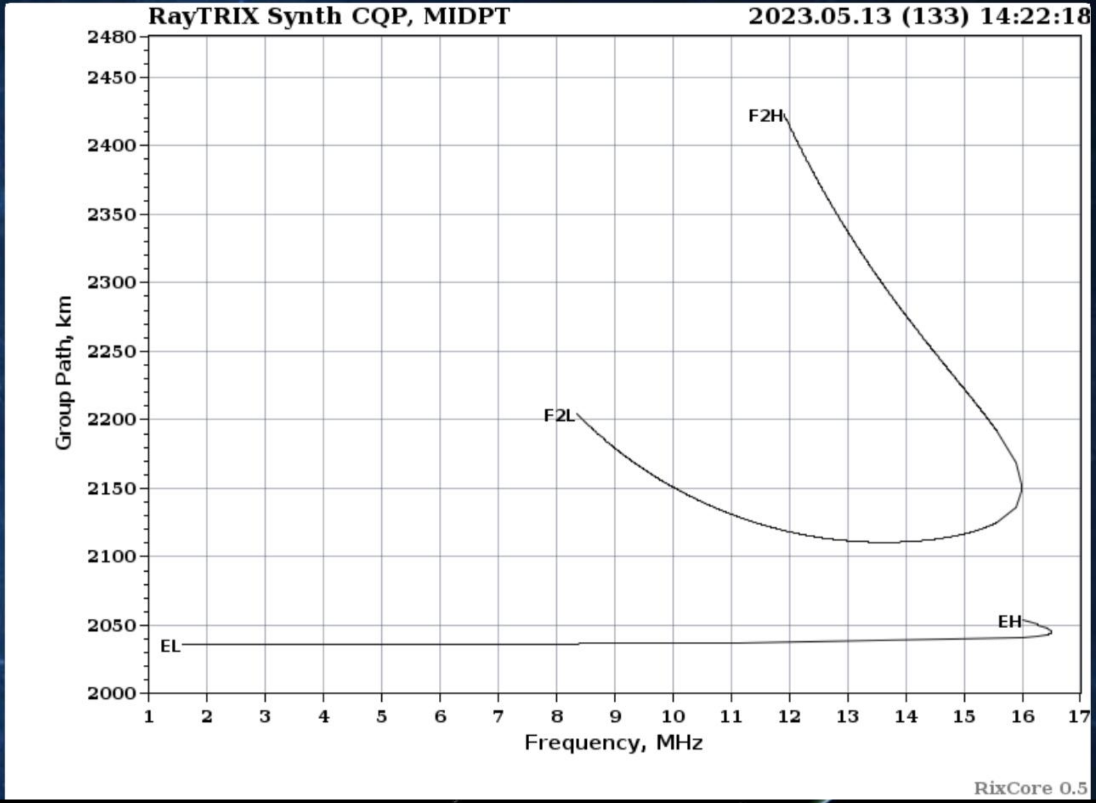
- Scalable to management of large number of radiolinks

RayTRIX CQP online

giro.uml.edu

RayTRIX
Ray Tracing through Realistic Ionosphere Explorer





RayTRIX-CQP: Oblique ionogram synthesizer with E, F1, F2 layer echo traces and MUFs, driven by IRTAM ionospheric nowcast

Description

Ray Tracing through Realistic Ionosphere eXplorer (RayTRIX) collection contains traces of remote high frequency signal propagating through E, F1, and F2 layers of the ionosphere for a given arbitrary time and radio link with one transmitter and one receiver. Also computed are values of the Maximum Usable Frequency (MUF)for each layer, defined as the maximum frequency at which communication between the end points of the given radio link is still possible. RayTRIX computes signal flight time (dependent variable) as a function of the operating frequency (independent variable). Computation is done using an analytical solution of the signal propagation through a plasma layer of the quasi-parabolic (QP) shape. RayTRIX-CQP represents the ionospheric channel as a composite of three QP descriptions for E, F1, and F2 layers at the mid point of the given radio link. The CQP plasma density profile is built by fitting QPs to the IRTAM assimilative model of the real-time ionospheric weather, available via GAMBIT database portal at https:/giro.uml.edu/GAMBIT.

Identifier

Local ID	DataCollection_RayTRIX-CQP
Namespace	pithia
Version	1
Created	Wednesday 2nd Feb. 2022, 15:00:00
Last Modified	Wednesday 2nd Feb. 2022, 15:00:00

Download

DataCollection_RayTRIX-CQP.xml

Path forward

- Improve IRTAM specification of weather
  - Additional measurements available in near real-time
    - Assimilation of data from moving platforms (spacecraft)
      - Radio occultation
      - GNSS
- Add 2nd hop computation to GPU algorithm
- Add evaluation of the signal strength
  - Ray geometry allows to assess path length through D region
  - D-region density diagnostics using digisonde signal strength data
- Forecasting IRTAM
  - Use helio- and geospace activity indicators to forecast storm impact
    - “MUF depression” alerts

HR-2006 Raytracing System

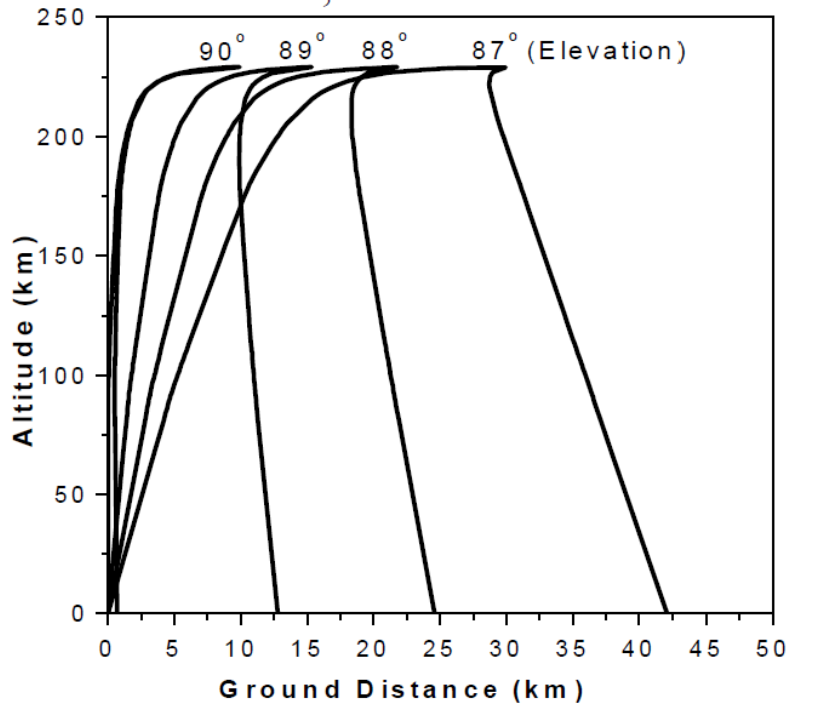
Huang, Xueqin, and Bodo W. Reinisch. "Real-time HF ray tracing through a tilted ionosphere." *Radio Science* 41, no. 05 (2006): 1-8.

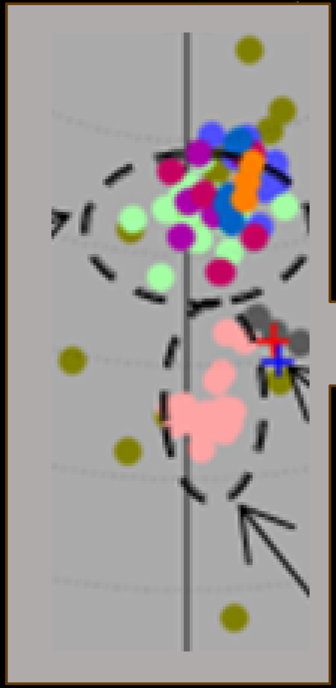
based on Haselgroove ray equations, © 1957

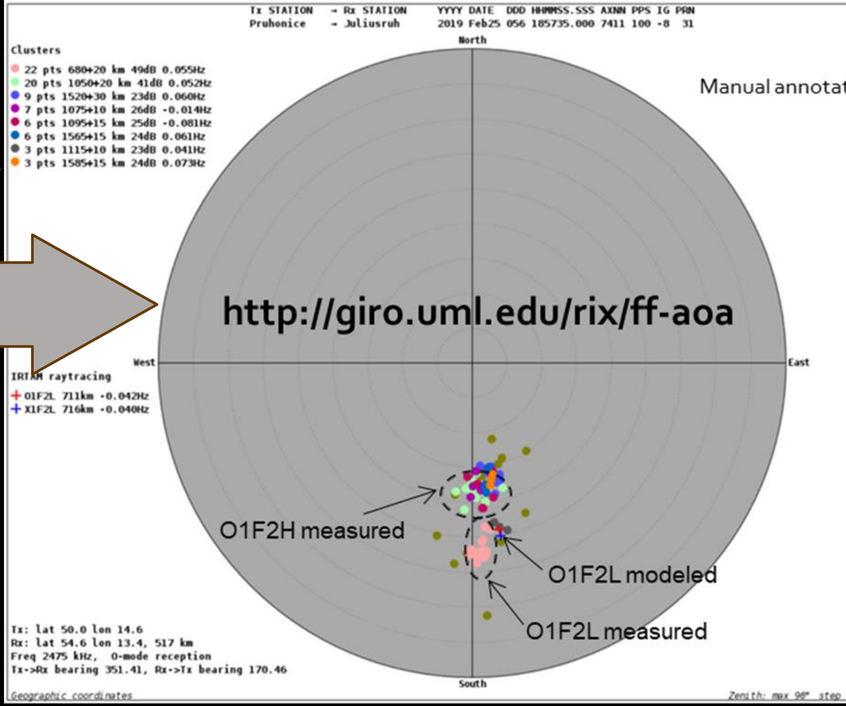
and general Snell’s Law for reflection/refraction

HR-2006 Ray-tracing

- Realistic Ionosphere!
  - Full 3D specification of the ionosphere between Tx and Rx
  - IRI formalism without simplifications
    - IRTAM weather can be used if available
- Spitze effect is explained
  - Responsible for the “short-range catastrophe”
- Superposition of TID waves on background ionosphere
  - Full TID specification
  - Doppler frequency computation supported







https://giro.uml.edu/rix/ff-aoa/

GIRO | Ionogram Data | Plasma Drift Data | TID Data | GAMBIT Weather Maps | Radio Link Evaluation | Examples | Info

RayTRIX

Ray Tracing through Realistic Ionosphere Explorer

FIXED FREQUENCY ANGLE OF ARRIVAL

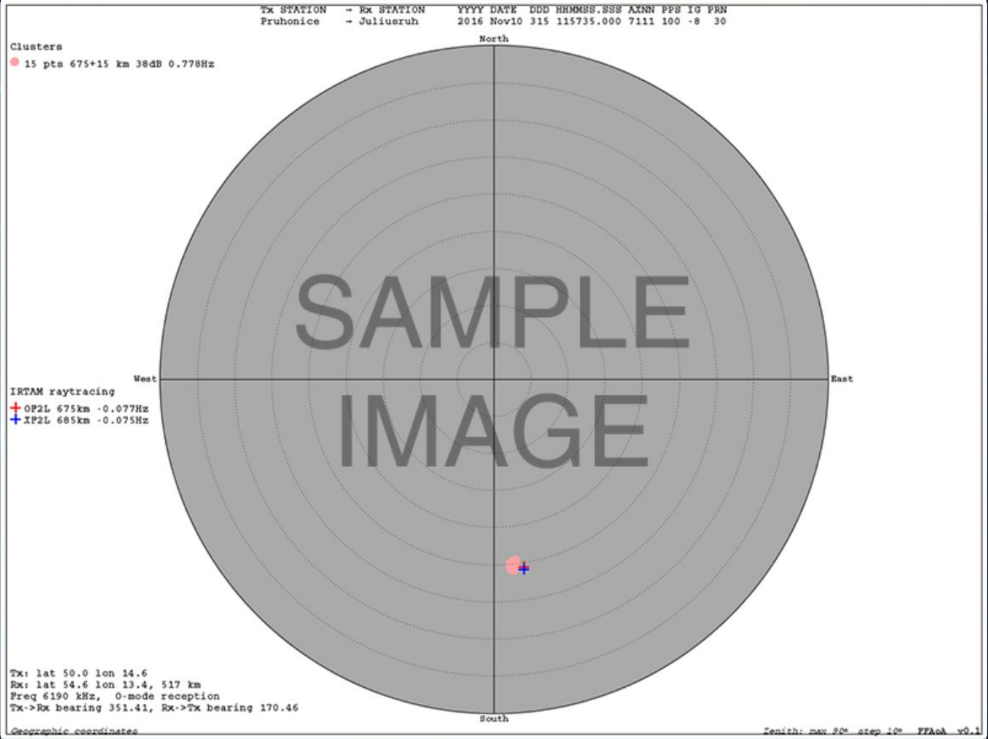
☐ Use Current Date and Time

Date: mm/dd/yyyy

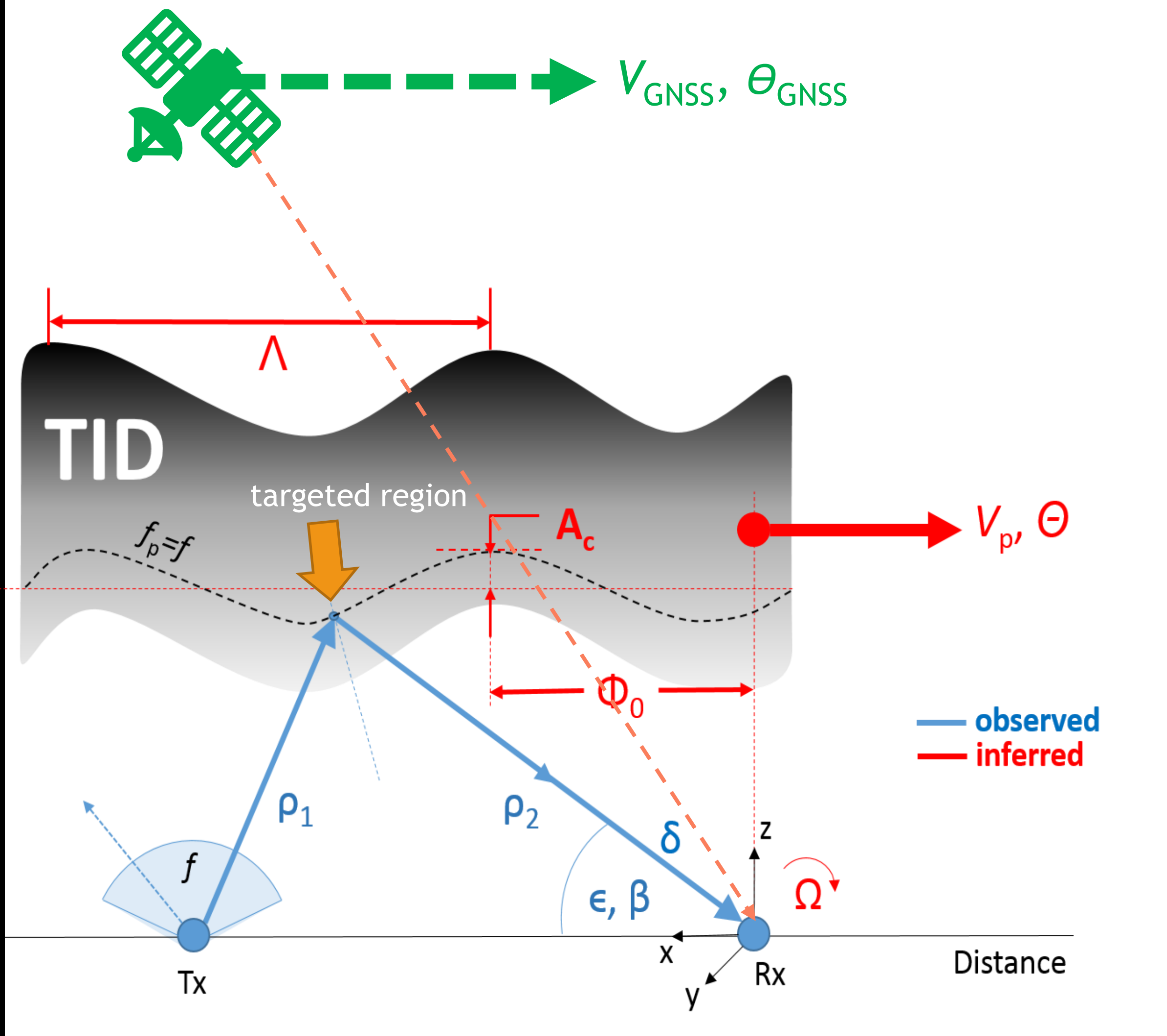
Hour: 00 | Minute: 00

Path: PQ052 to JR055

Calculate

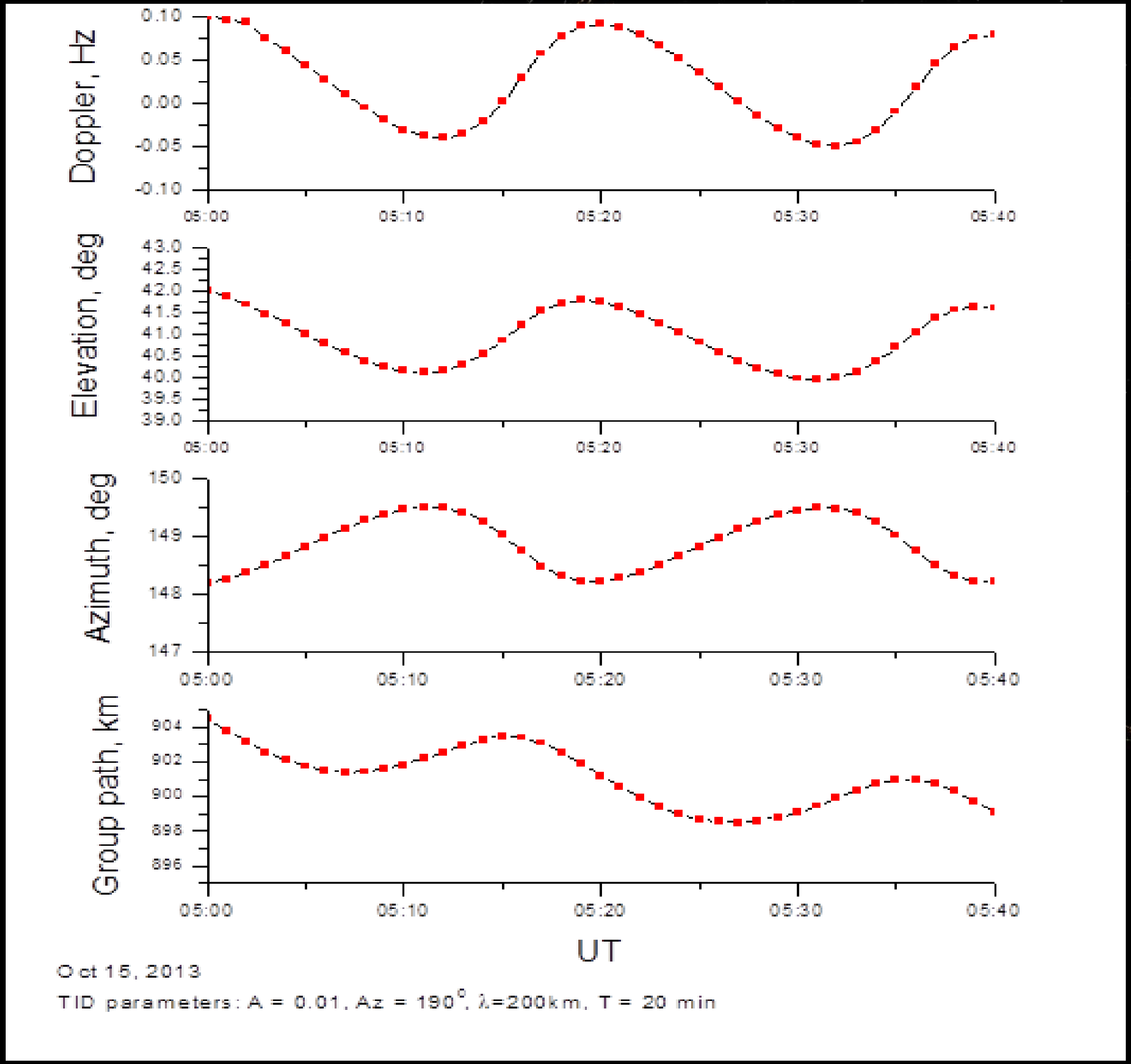


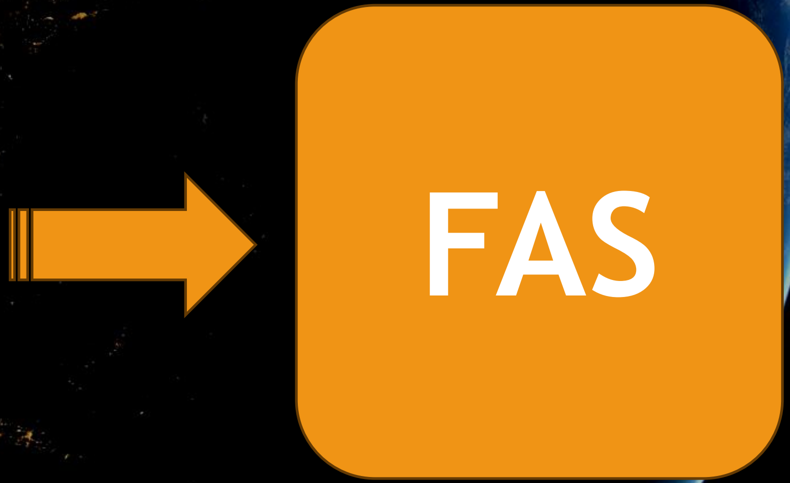
RayTRIX HR-2006: modeling tool for TID evaluation



- Stationary "reference" begins *fluctuating* with certain period Ω
  - Reference Rx for GNSS: its own location fluctuates
  - HF-Radar: reference Tx loc fluctuates
  - Travels fast
- Corrections need to be evaluated and disseminated
  - Not always possible

HR-2006 model of signal in TID presence





https://dispec.eu

The DISPEC Project

Scientific exploitation of space Data for improved Ionospheric SPECification (DISPEC)

The **DISPEC project** offers new high-level data products based on advanced data processing techniques that improve data quality, provides estimates of ionospheric characteristics based on the joint processing of space and ground data, provides results from post-processing of data for improved ionospheric specification, and exploits long-term time series for the study of long-term trends in the ionosphere in connection to atmospheric long-term dynamics and geophysical phenomena. Specifically, DISPEC derived high-level data products aim at:

- Providing fast processing of time series that lead to curated data.
- Deriving new high-level data products based on the exploitation of raw data from multi-locations and multi-instruments, useful for input to ionospheric specification models.
- Deriving new ionospheric indicators based on the post-processing of raw satellite and ground-based instruments' data useful for a quick mapping of ongoing ionospheric irregularities.
- Providing proxies for geophysical phenomena and long-term trends in the ionosphere.

Objectives

The main objective of DISPEC project is the exploitation of bottomside and topside ionospheric data, provided by space missions – such as Swarm, DORIS, GRACE, GRACE-FO, Spire, COSMIC-2– and by ground-based GNSS receivers and ionosonde sounders, to support research activities for improved ionospheric specification, through the derivation of high-level data products. The project outcomes have the potential to complement the ESA Space Science Archives and the Space Weather Network, the data collections provided by the global networks of ionosondes and GNSS ground based receivers, and to enhance the capacity of European Research Infrastructures.

To meet the main objective of the project, it is necessary to address the following specific objectives:

« February 2024 »

Mo	Tu	We	Th	Fr	Sa	Su
29	30	31	1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	1	2	3

News

DISPEC Kick-off Meeting

Feb 07, 2024

More news...

Take home messages

- Scenarios for HF signal modeling (by raytracing):
  - HF Geolocation
  - Frequency management for HF Communications
  - Over-the-horizon radar
  - Simulation of TID overpasses
- PITHIA-NRF registered RayTRIX CQP data collection
  - Synthesizes full oblique ionogram frame for any given TX and RX
    - Running time – a few seconds per ionogram
  - Mated to IRTAM weather nowcast
  - MUFs and least-multipath band are computed for operational use
- HR-2006: a signal modeling testbed for TID detection using D2D