REALISTIC RION IONOSPHERE

Realistic Ionosphere

with concepts for AI-driven ionosphere forecast

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Realistic Ionosphere, United Nations ISWI
Space Science Laboratory, UMass Lowell
Global Ionosphere Radio Observatory
Lowell Digisonde International, LLC
GAMBIT Situation Room

UML SPACE SCIENCE LAB

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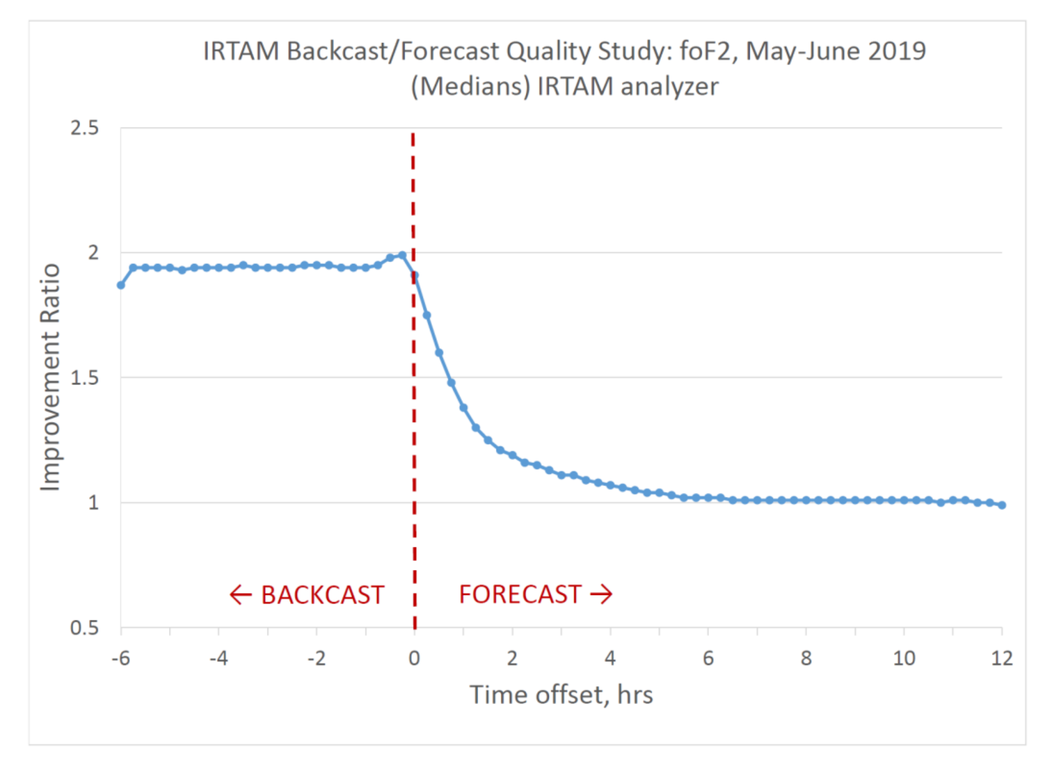
    - David Kitrosser
    - Steve Mendonca

Prelude

Ionosphere (*def.*): a major operational nuisance. © AFRL

Prelude (cont.)



- Ionosphere does not inform itself about its future state
- 4-hour old sensor data are useless
- 1-hour old sensor data lose 50% of their value

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Outline

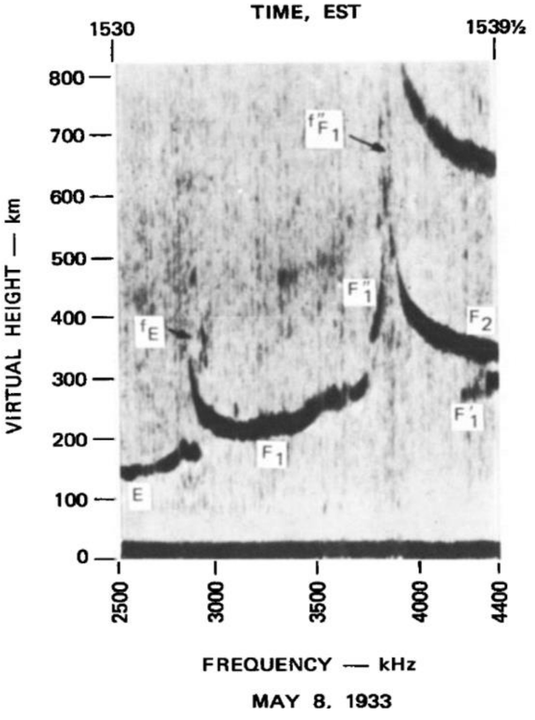
- RION "Instrument" Suite at UN ISWI
  - Review of its "weather monitoring" value
    - Ionograms: DIDBase with Portal and SAO Explorer
      - New: D-region specification
    - IRTAM and GAMBIT: Database and Explorer
      - HF Depression Analytics for ICAO
        - IRTAM maps of MUF(3000)
        - GAMBIT maps of Slab Thickness
    - RayTRIX: HF signal propagation modeling by raytracing
    - TID Explorer: detection and evaluation of TIDs
    - SkyLITE: plasma drift monitoring
- Natural Language Processing: a concept study for forecasting the ionosphere

RION is Home of Digisonde 4D

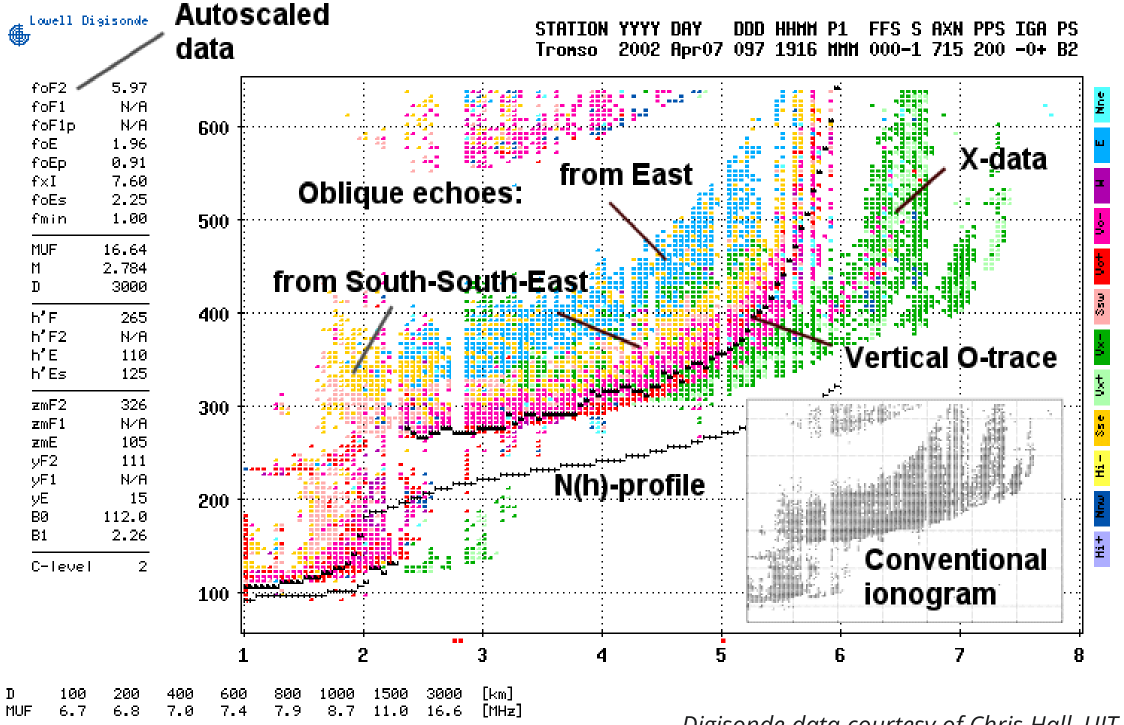
67 Digisonde 4D units built since 2007

- 1925: First ionosondes
  - Two models in UK and US
- 1936: Four ionosondes in the world
- 1957 (IGY): ~135 ionosondes
- 1969: First Digisonde
- Total ionosondes built: ???
  - Total ionosonde sites in NOAA: 231
  - so, maybe 500-600?
- 192 Digisondes built in Lowell; ~ 1/3 of world production

Ionogram in 1933 and nowadays



Credits to: Theodor Gilliland, NBS, USA



Digisonde data courtesy of Chris Hall, UIT

GIRO as of June 12, 2024

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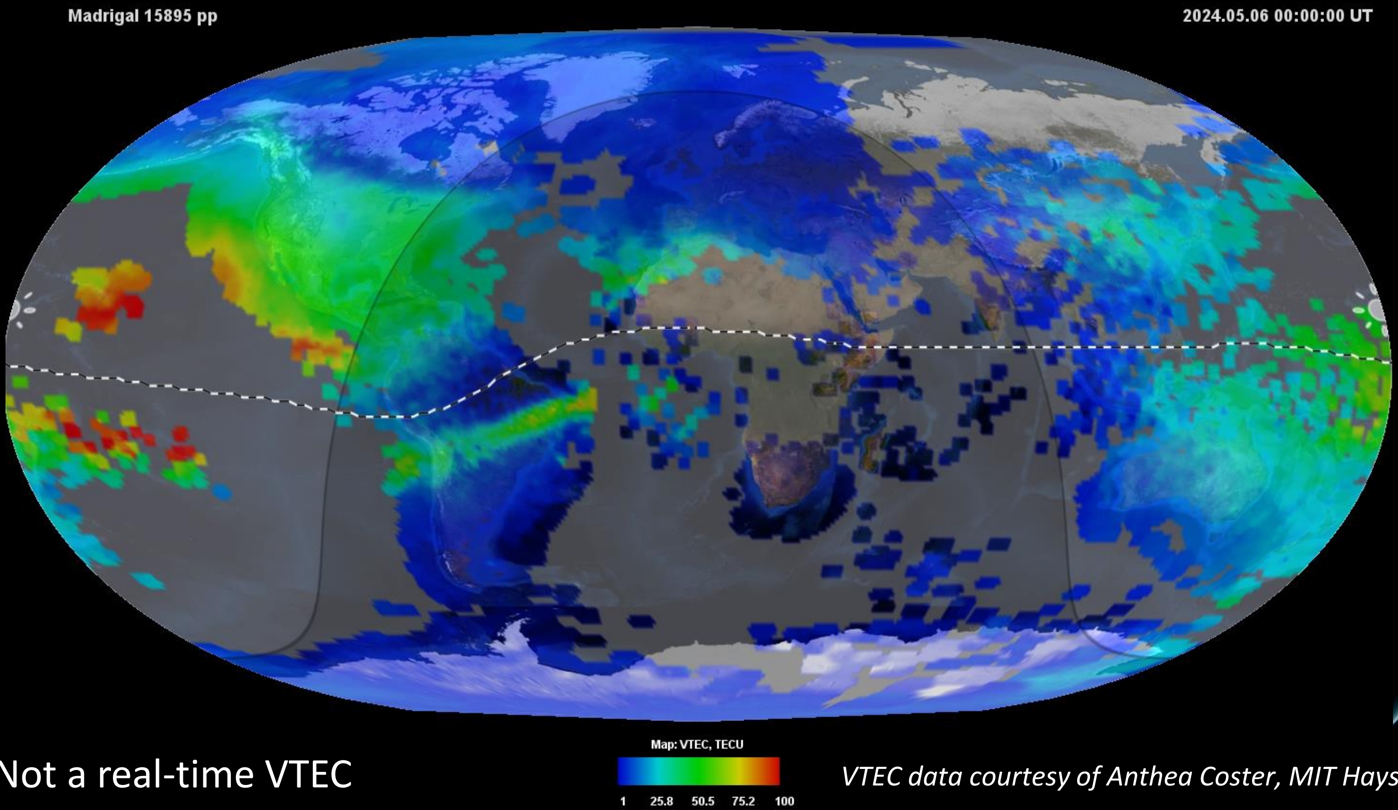
GIRO vs VTEC in CEDAR Madrigal



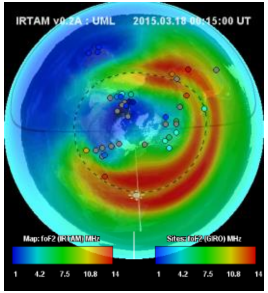
Not a real-time VTEC

VTEC data courtesy of Anthea Coster, MIT Haystack Observatory

UML Realistic Ionosphere

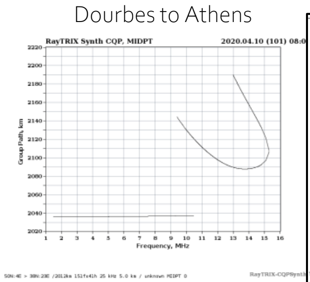
GIRO

including DIDBase

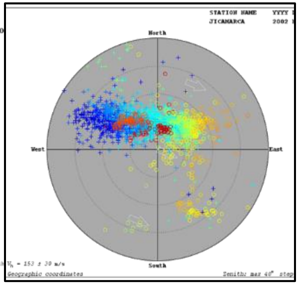


GAMBIT

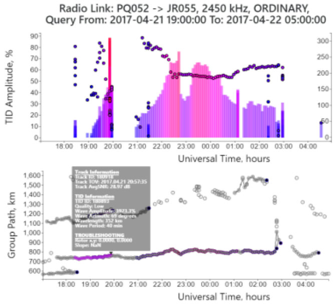
including IRTAM 3D



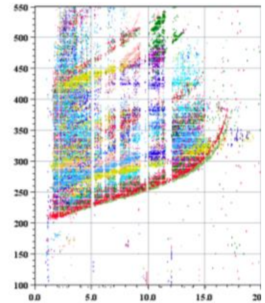
RayTRIX



SkyLITE



TID Explorer



IDI

0.Measurements

1. Global Weather Modeling

2. HF Signal Raytracing

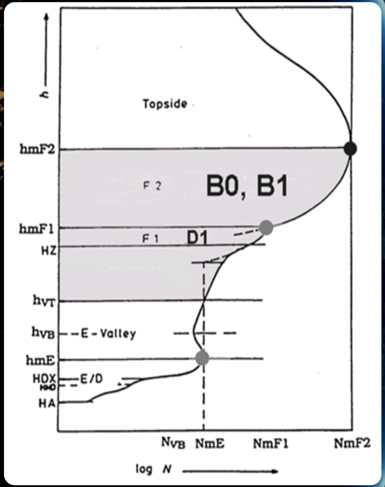
3. Plasma Drifts

4. TID Warnings

5. Disturbance Indicator

1. Real-Time IRI

- Real-Time IRI Task Force
  - founded in 2009
  - concept: tweak IRI using available observations
    - To make a good model better
    - Not necessarily an assimilation
      - Real-time IRI" simply refers to application to space weather
- IRTAM is IRI-based Real-Time Assimilative Model
  - A GRAY BOX approach (physics-informed)
    - IRI background is responsible for capturing underlying geophysics with solar, seasonal, and geomagnetic field dependencies
    - IRTAM merely *adjusts* IRI background 1-DITL
    - IRTAM represents observations faithfully
    - IRTAM gradually returns to the background over no-sensor regions



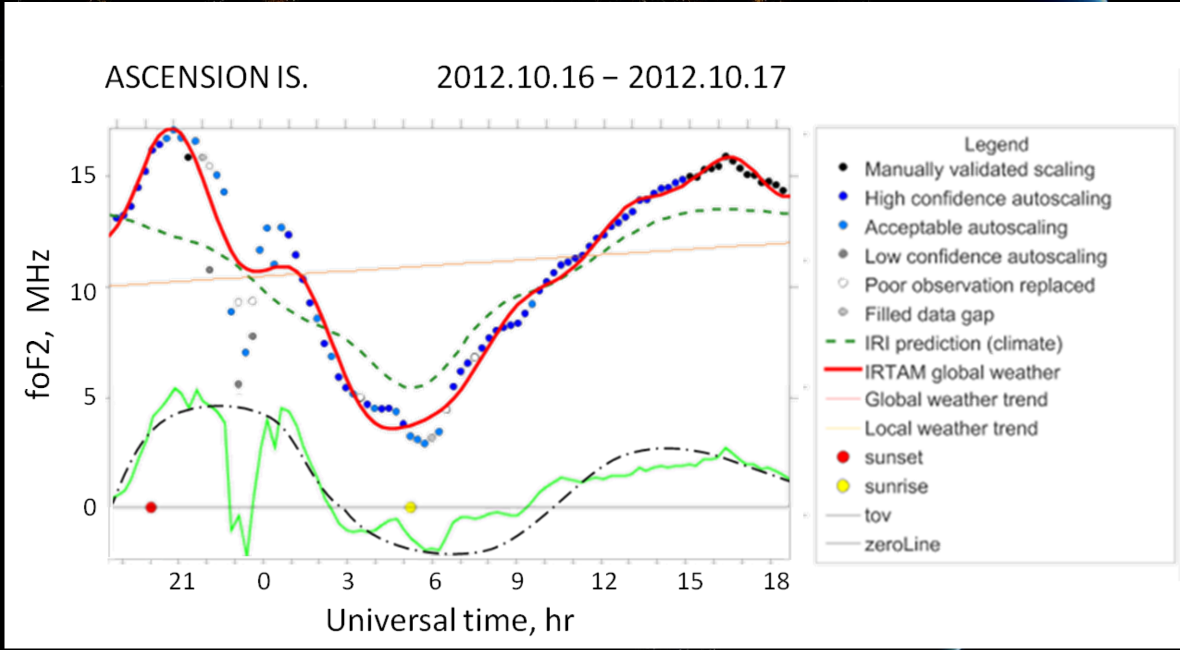
The vertical profile of plasma density:

16 "anchor" parameters

NECTAR

Morphing IRI using diurnal harmonics of anomaly dynamics

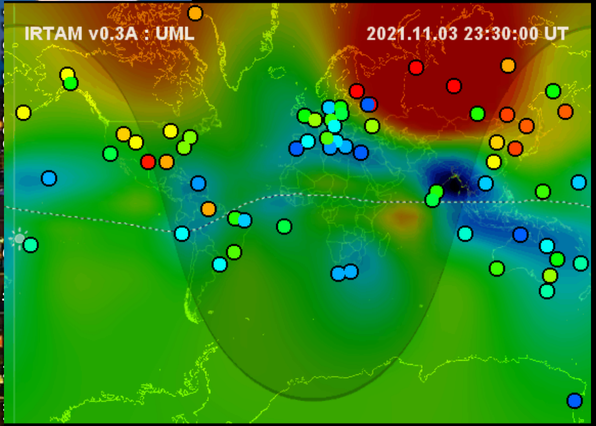
- NECTAR is not quite a Kalman filter
  - Significantly 4DDA
  - 24 hours of previous anomaly as observed at sensor sites
    - And then use diurnal harmonics os these anomalies
- Suppose a GIRO ionosonde detects a significant 12-hour deviation *Δ*. Question: how far from the site this correction shall extend?
  - How about 4-hour harmonic?



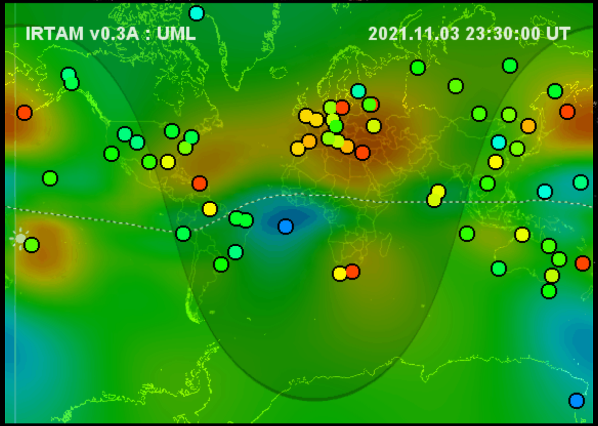
Nov 4, 2021 Storm, Kp ~ G3..G5

GIRO ionosondes only, IRTAM 3D assimilative model

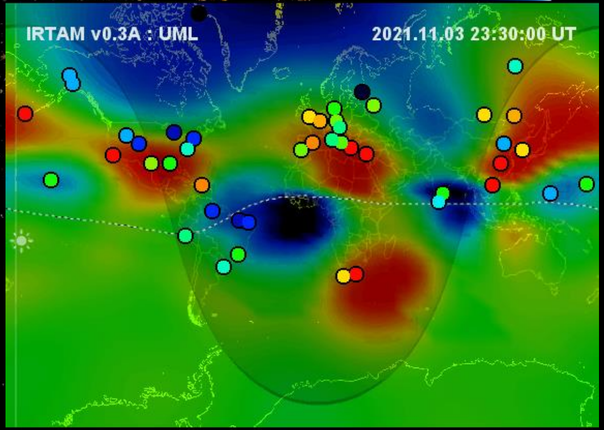
NOT A SIMULATION



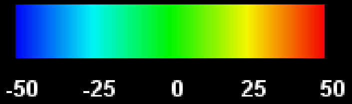
Δ foF2



Δ hmF2



Δ B0



“Anomaly map” = Percent Deviation from Quiet Conditions

Gambit eXplorer

REALISTIC RION IONOSPHERE

Free for academic use: GAMBIT Explorer UserApp 1.0A
Download from https://giro.uml.edu/GAMBIT/

GAMBIT EXPLORER

ACCESS TO IRTAM DATA

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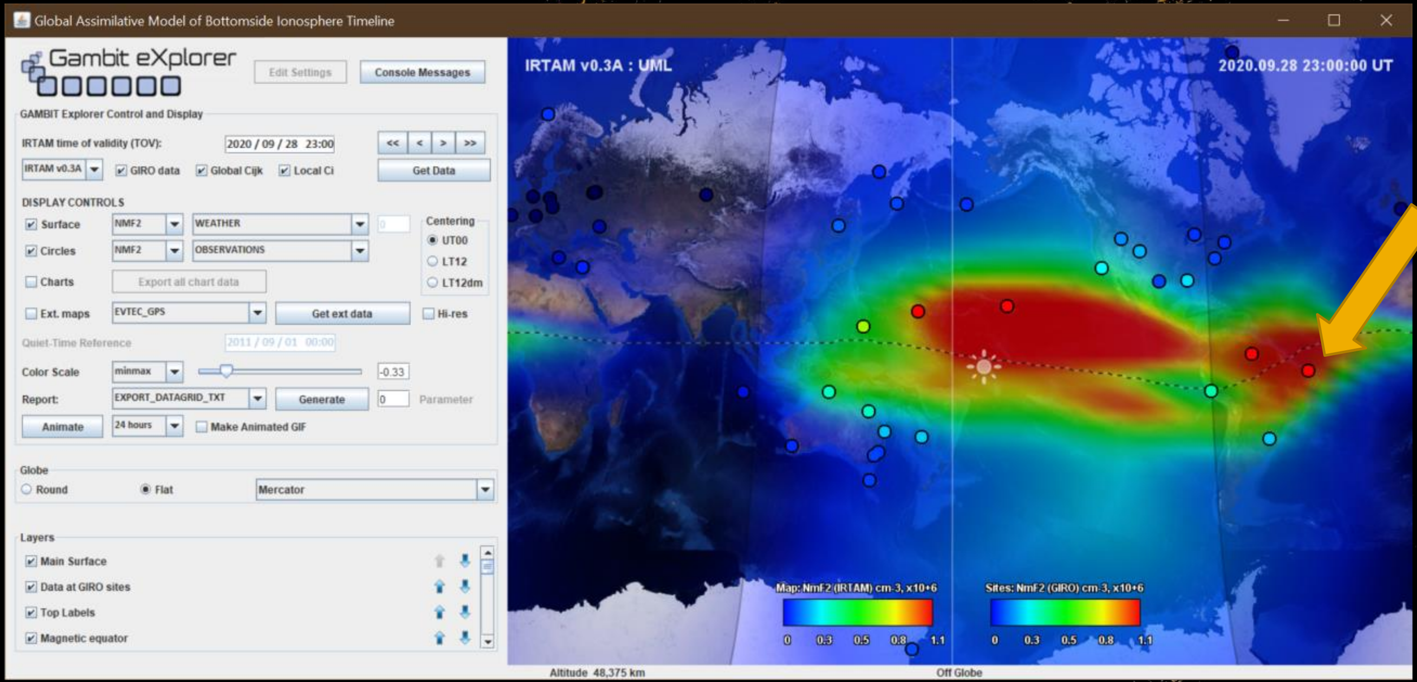


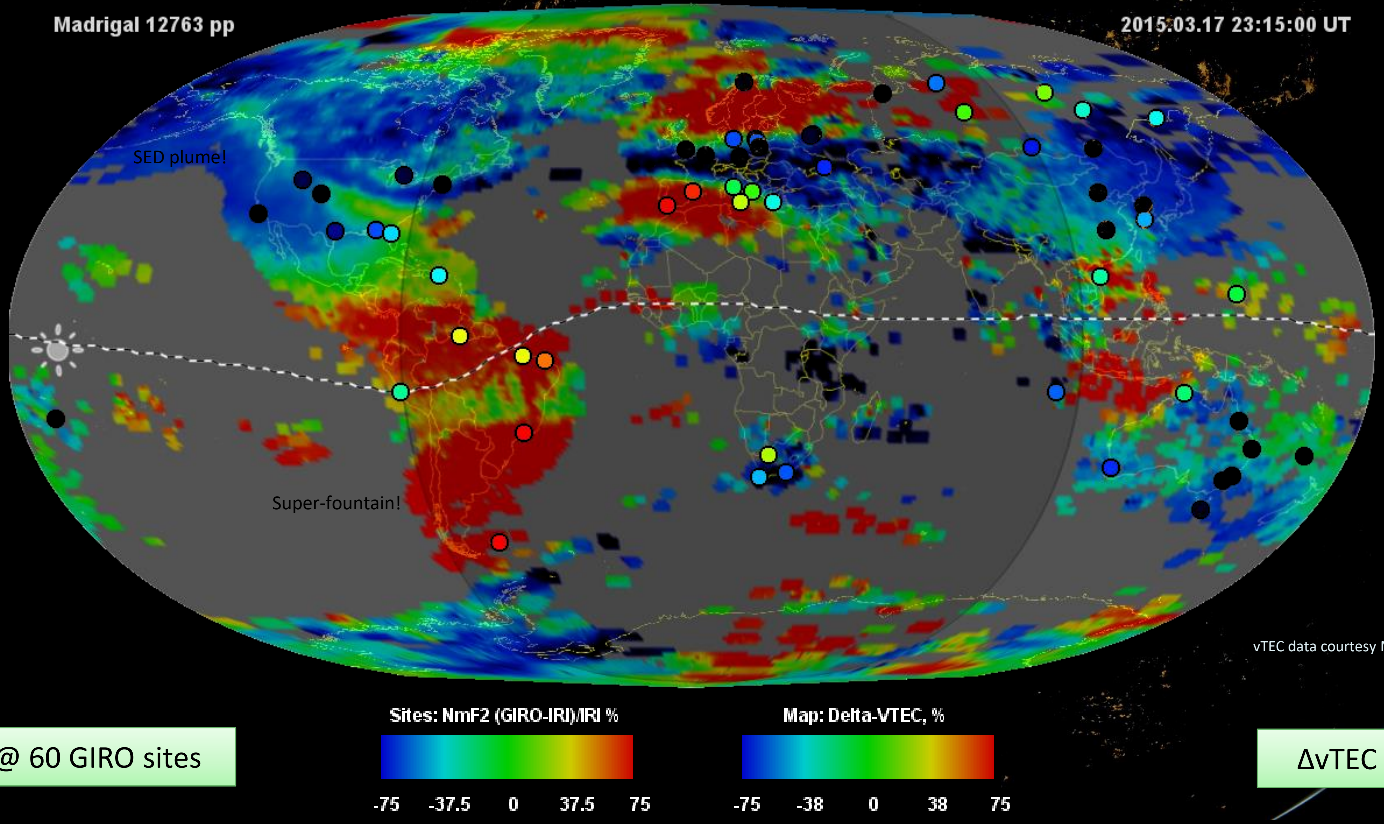
CLICK FOR DETAILS

+ source code to integrate IRTAM coefficients from GAMBIT database with user applications

UMASS LOWELL

Anomaly maps by IGS and GIRO

St. Patrick storm of March 17, 2015 23:15

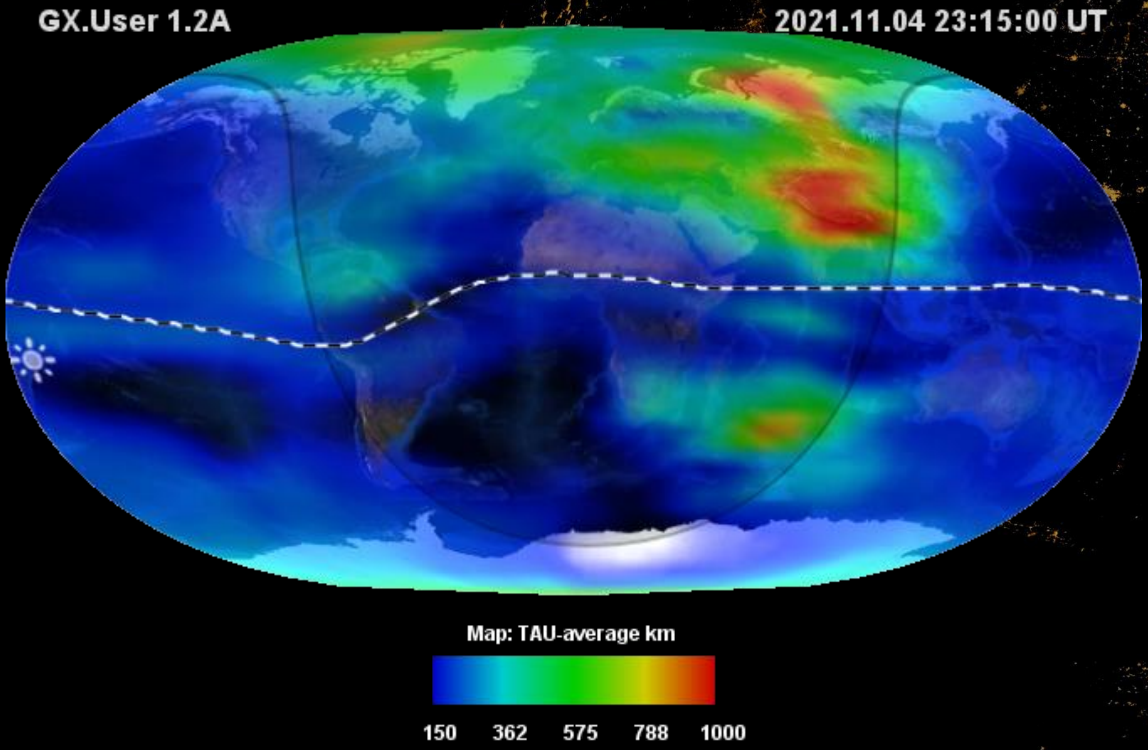


Gambit eXplorer
giro.uml.edu/GAMBIT

ΔNmF2 @ 60 GIRO sites

ΔvTEC @ 6342 GNSS sites

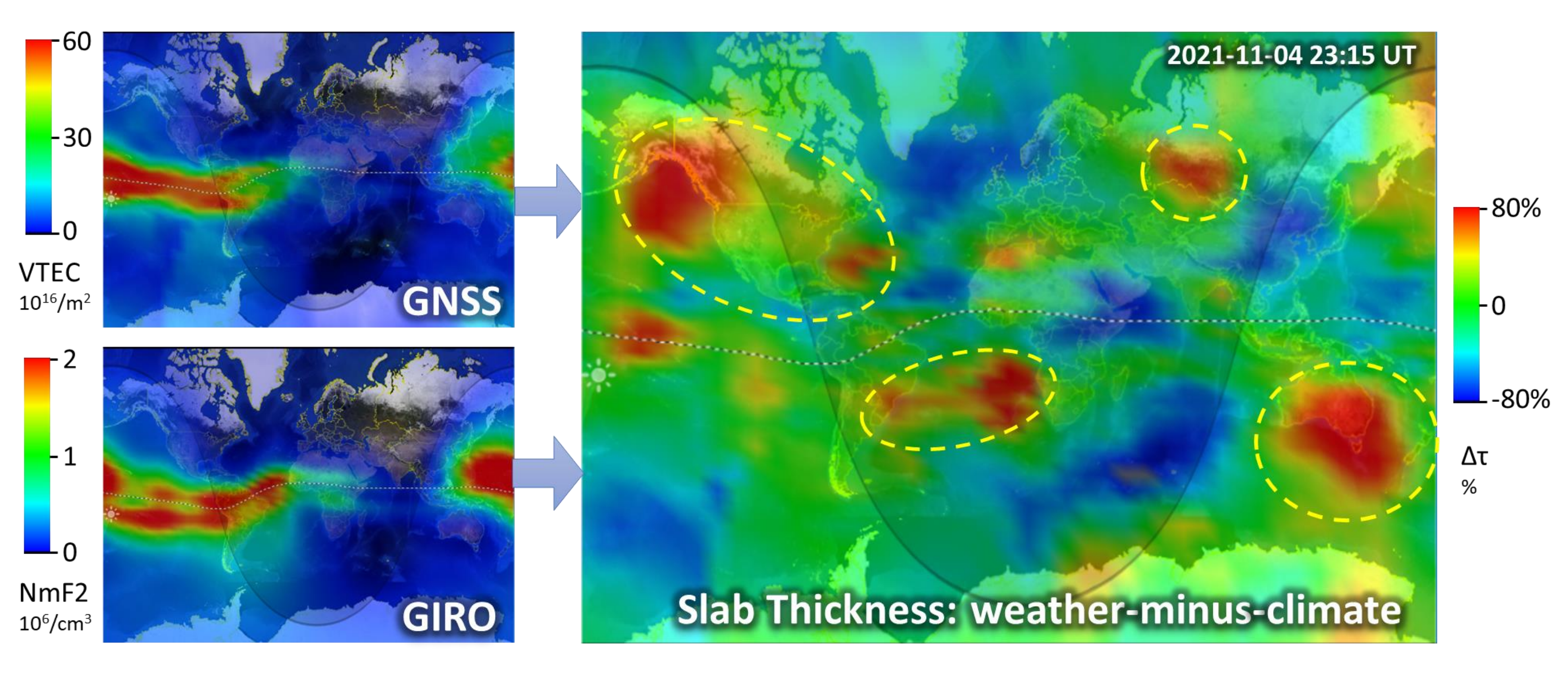
Slab Thickness Climatology



NmF2: IRI foF2 model (climate)
VTEC: IGS 30-day median VTEC

[Fron *et al.*, 2020]

Real-time Anomaly Slab Thickness



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2. RayTRIX CQP

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~5 sec running time

RayTRIX

Ray Tracing through Realistic Ionosphere Explorer

OBLIQUE TRACE SYNTHESIZER

Choose station pair or type coordinates below.

Station Pair: PQ052 to JR055

Transmitter Coordinates:

50 N (-90..90)

14.6 E (0..360)

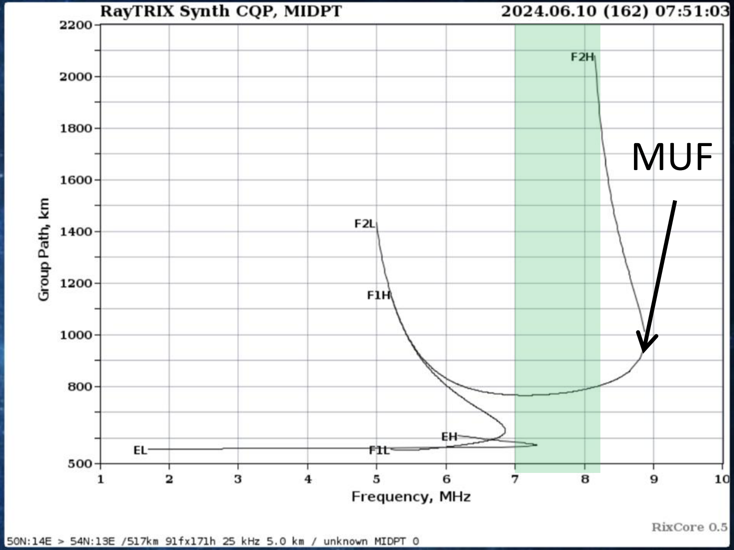
Receiver Coordinates:

54.6 N (-90..90)

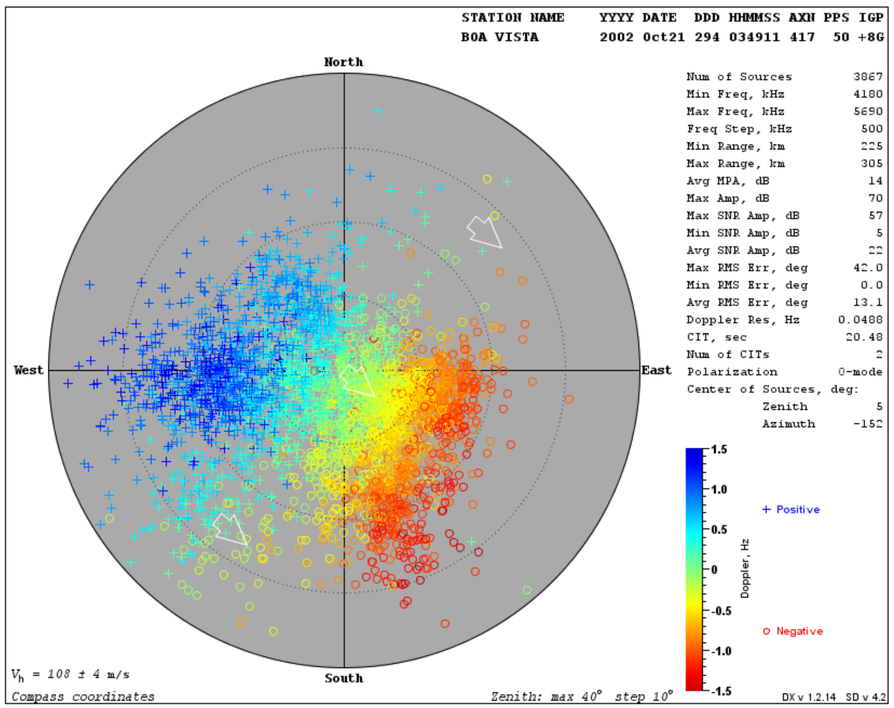
13.4 E (0..360)

☑ Use Current Date and Time

Date: mm/dd/yyyy

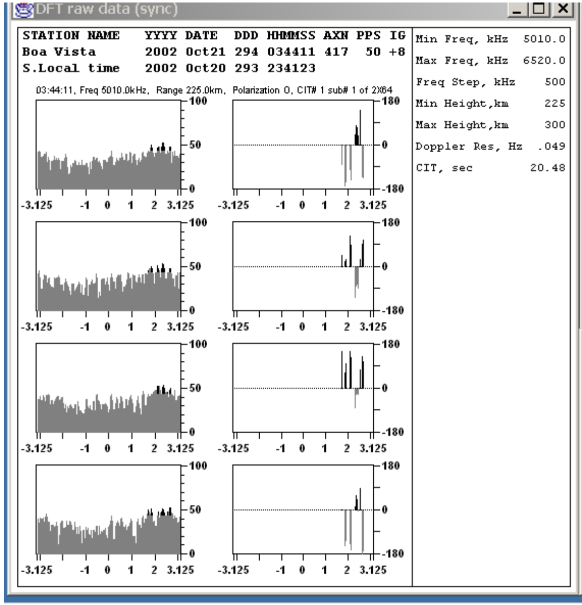


3. Doppler Skymapping of Ionosphere

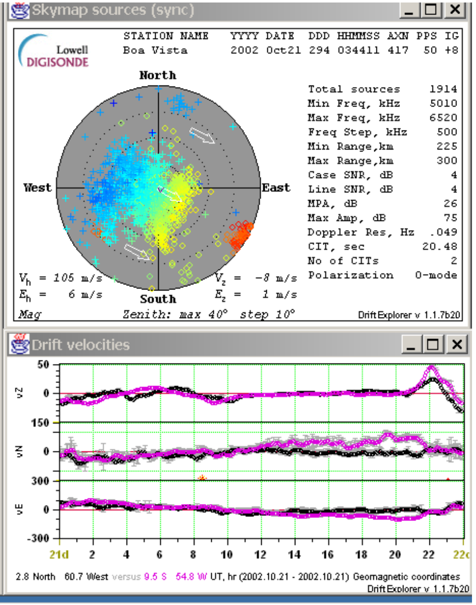


- Digisonde illuminates all sky above the station
- If the ionosphere is flat and undisturbed, the only echoes will come from the zero zenith in the skymap center
- Off-vertical echoes are possible if plasma irregularities exist of the right scale and orientation
- Doppler frequency analysis allows determination of the plasma density drift vector

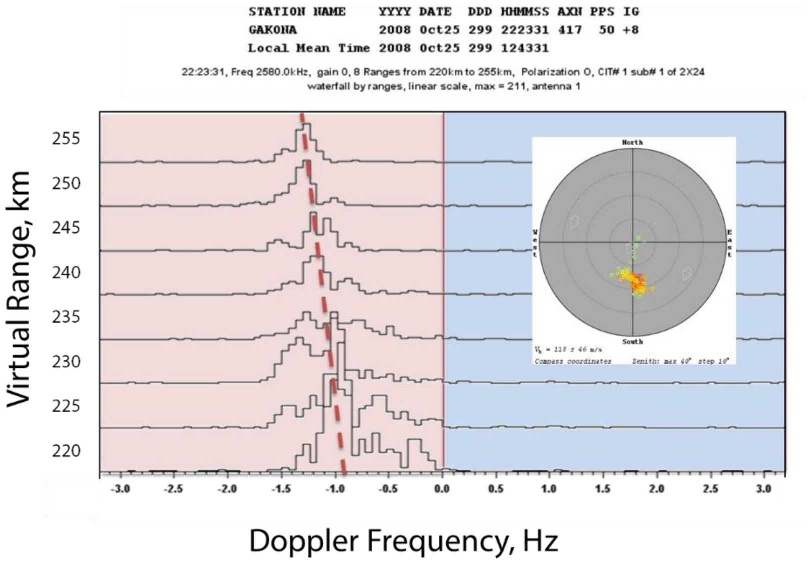
Plasma Drift and SkyLITE



4-channel data



Skymap & Vector Drift Velocity



HAARP Heating Experiment

Boa Vista skymaps courtesy of Inez Batista, INPE

Gakona skymaps courtesy of

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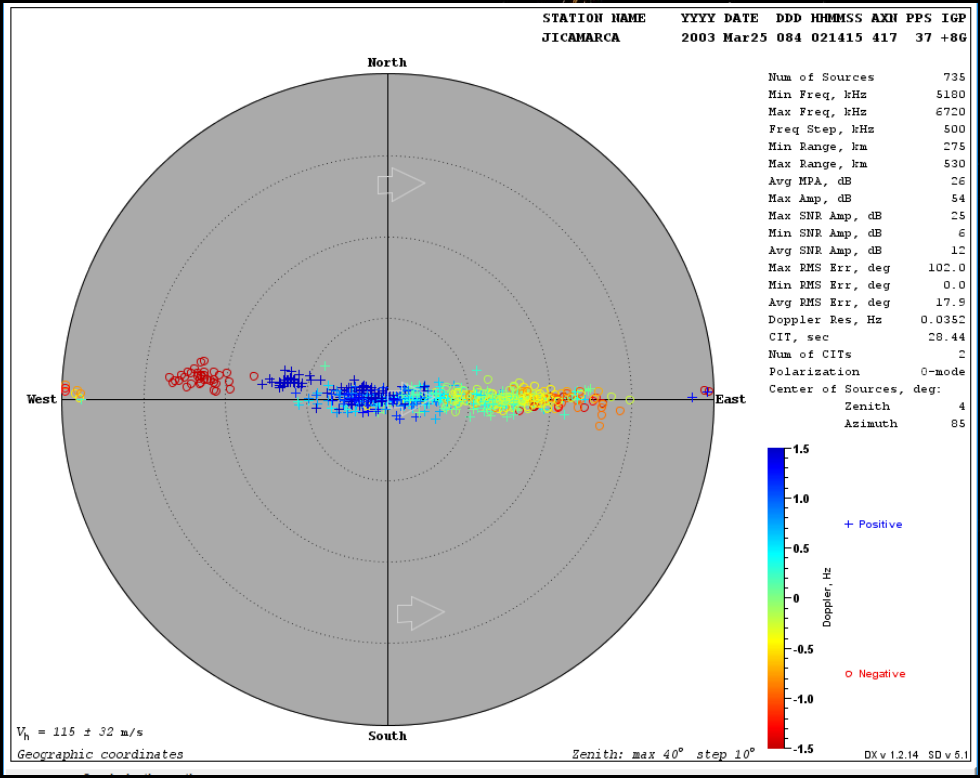
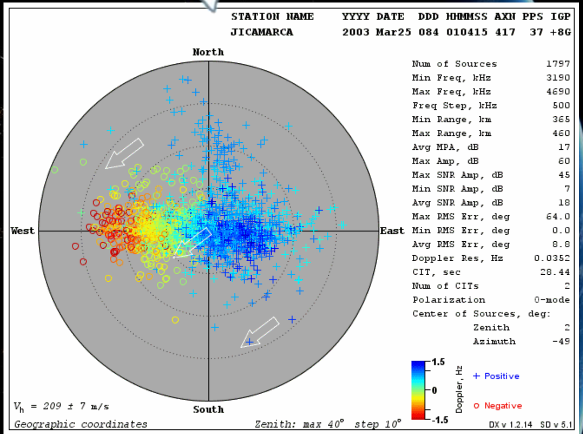
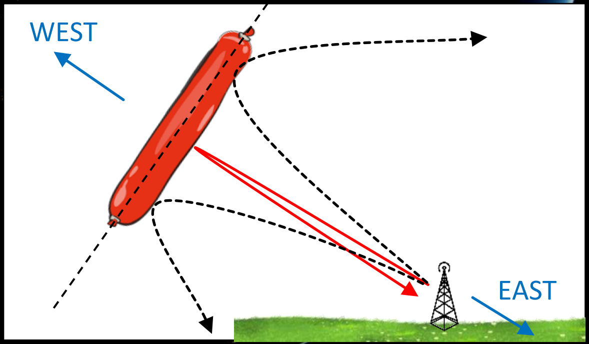
Sausages in the Sky?







Jicamarca skymaps courtesy of Oscar Alfredo Veliz Castillo, JRO

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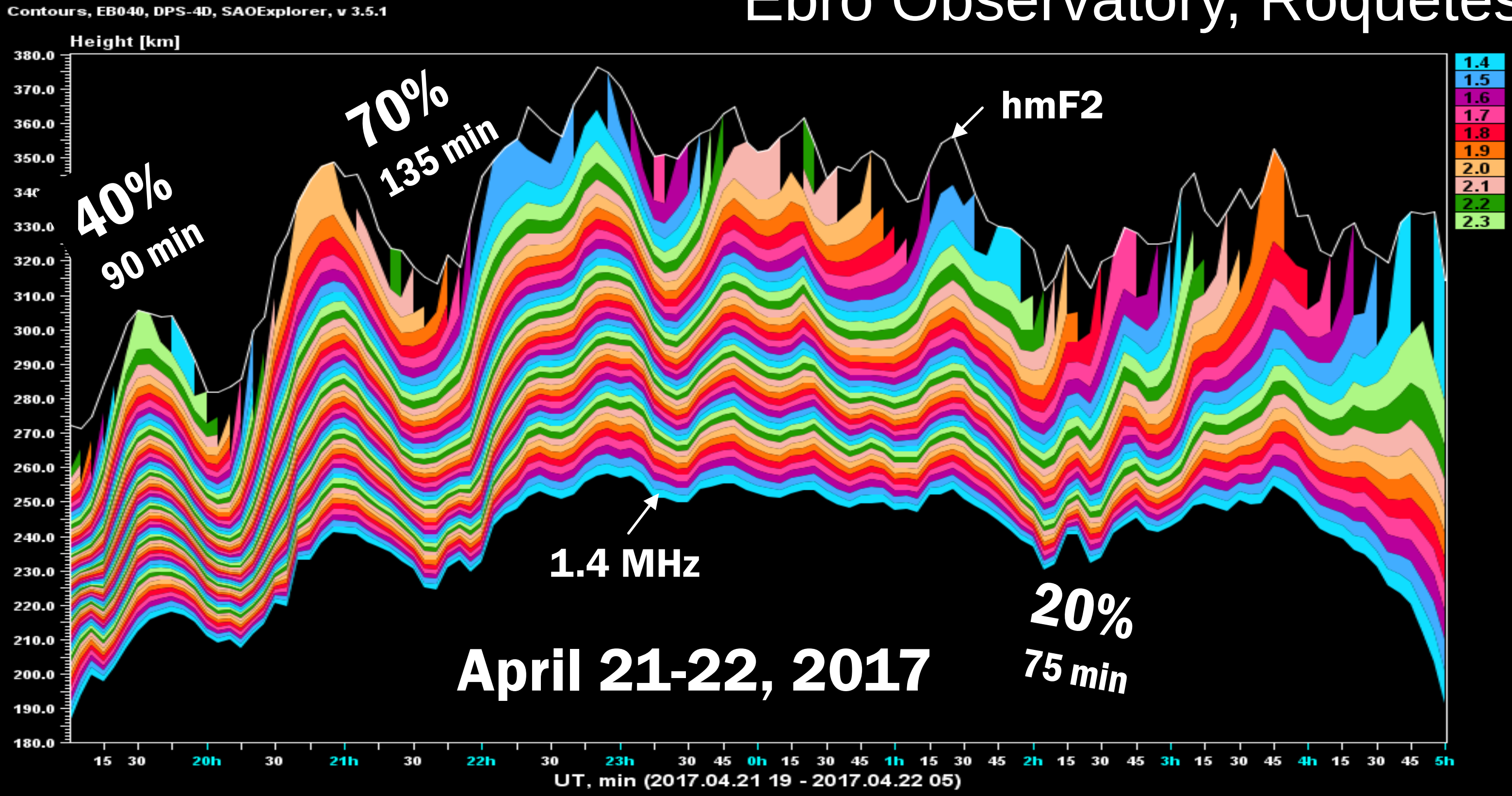
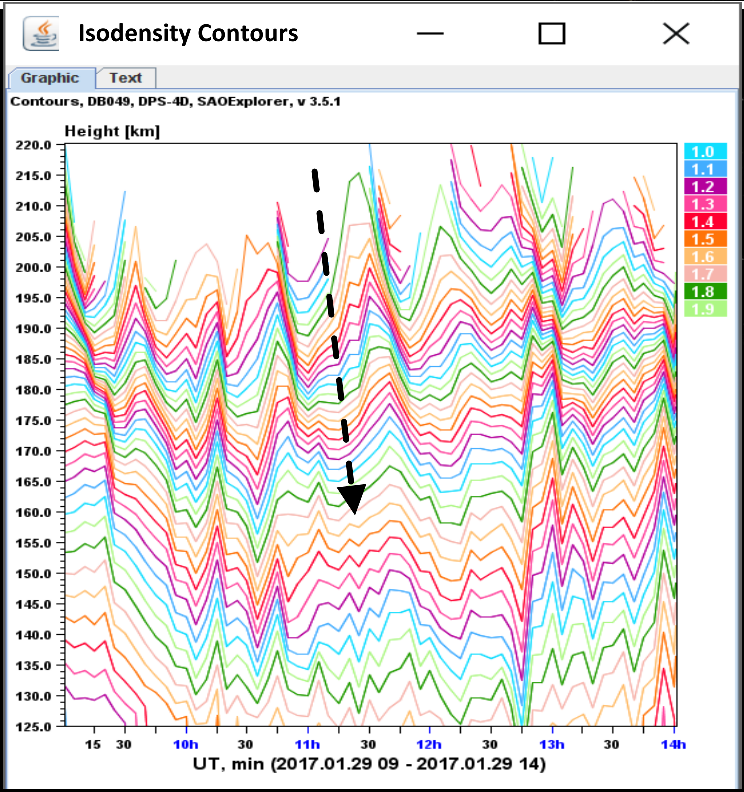
UMASS LOWELL

4. TID Detection

Ebro Observatory, Roquetes



HF versus other TID sensors

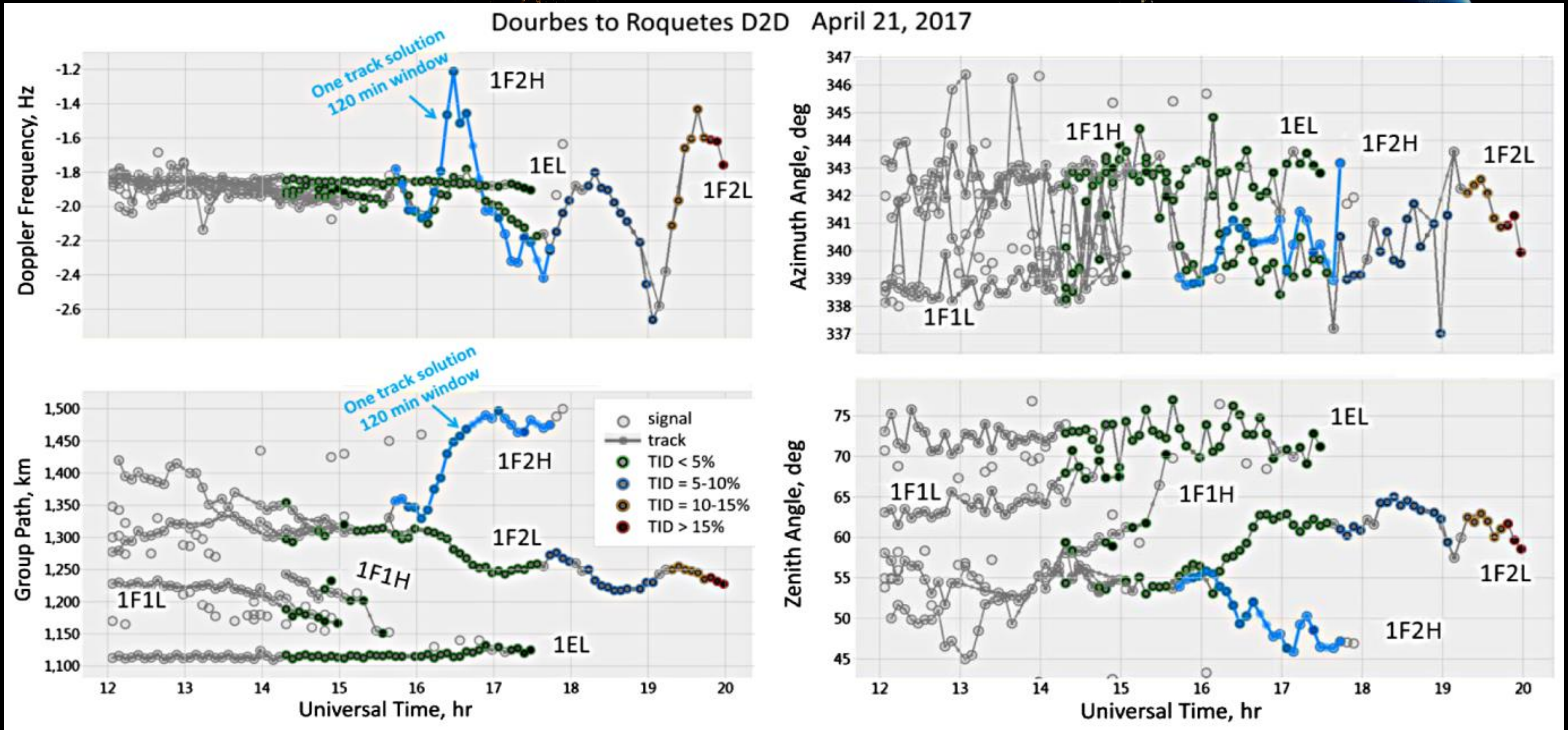


Data courtesy Tobias Verhulst, RMI

- **1D Altitude profile of TID**
  - Detailed view of propagation along z-axis
  - Pin-point to particular altitude region
- **Sensitivity**
  - Detection of a 5% TID vs underlying density
  - “TID are always present” < 1%
- **Direction, Velocity, Wavelength**
  - **HF-TID method**
- **Direct measurement**
  - Static platform (no motion effects)
  - No slant-to-vertical transformation needed
- **24/7 operations with automatic intelligent system analysis**
  - Replicate human intelligence

Automatic Signal Tracking

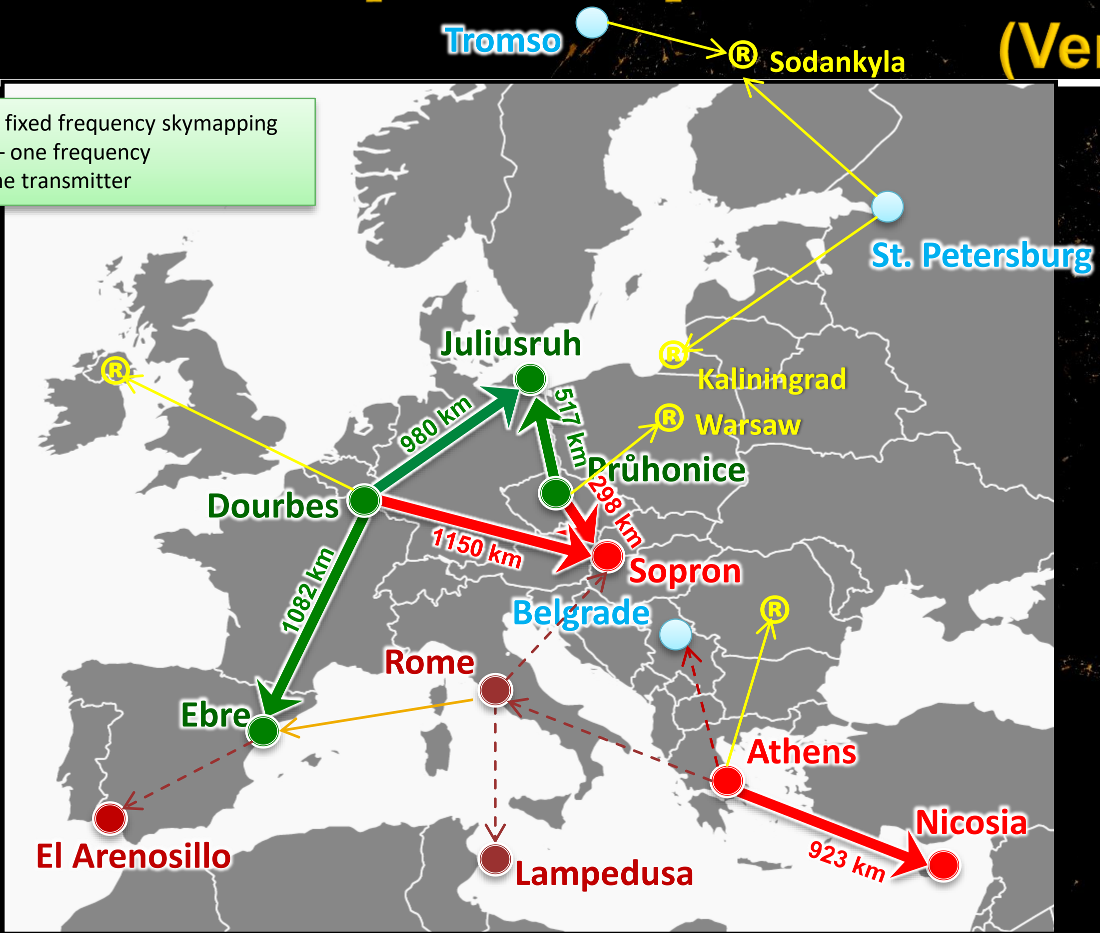
Dourbes to Roquetes link (1082 km) ["southern link"]



European pilot D2D network

(Verhulst *et al*., 2017)

TID tracking: D2D fixed frequency skymapping
One transmitter – one frequency
One receiver – one transmitter



Phase I links

Phase II links

Upcoming DPS4D sites

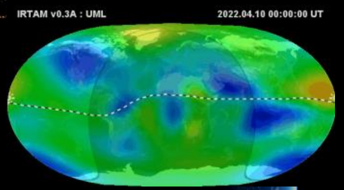
Potential DPS4D sites

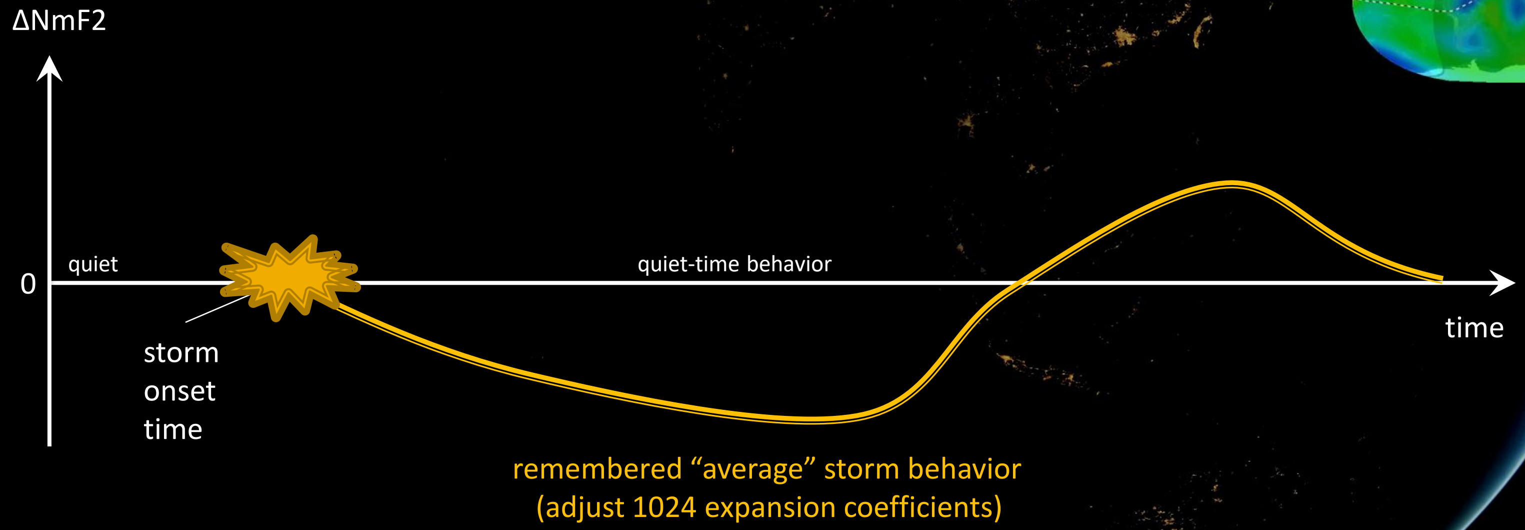
Possible DPSR sites

Forecasting Ionosphere

Using Natural Language Processing (NLP) approach

“Triggered” storm option in IRI





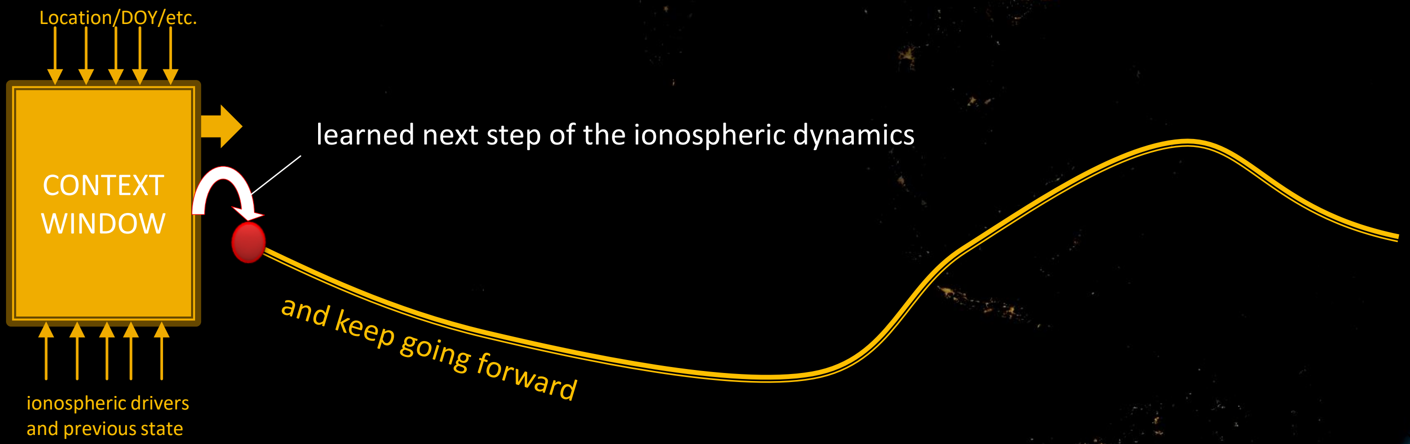
Forecast by analogy to an average “anomaly” storyline

Next: Library of the storm storylines

instead of the "average storm timeline"

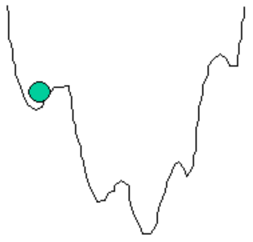
- Instead of an "average" storm, keep a library of previous storylines of ΔNmF2 anomalies
  - NOT to build a least-square regression on 1024 unknowns
  - NOT to build a back-prop feed-forward NN with 1024 outputs
  - Just memorize them, *cleverly*
  - To forecast, look for the most relevant storm ΔNmF2 in the library
- Each library storyline must be relevant in the context of the ionospheric drivers
  - i.e., not just replay of the storm using one "trigger"
  - Need to build them against an external storyline of events in the heliospace and geospace
- Need good ideas for
  - The storm library
  - Search-and-retrieval algorithms
  - *Tweaking the library copy to current conditions*

“ChatGPT” for capturing the context

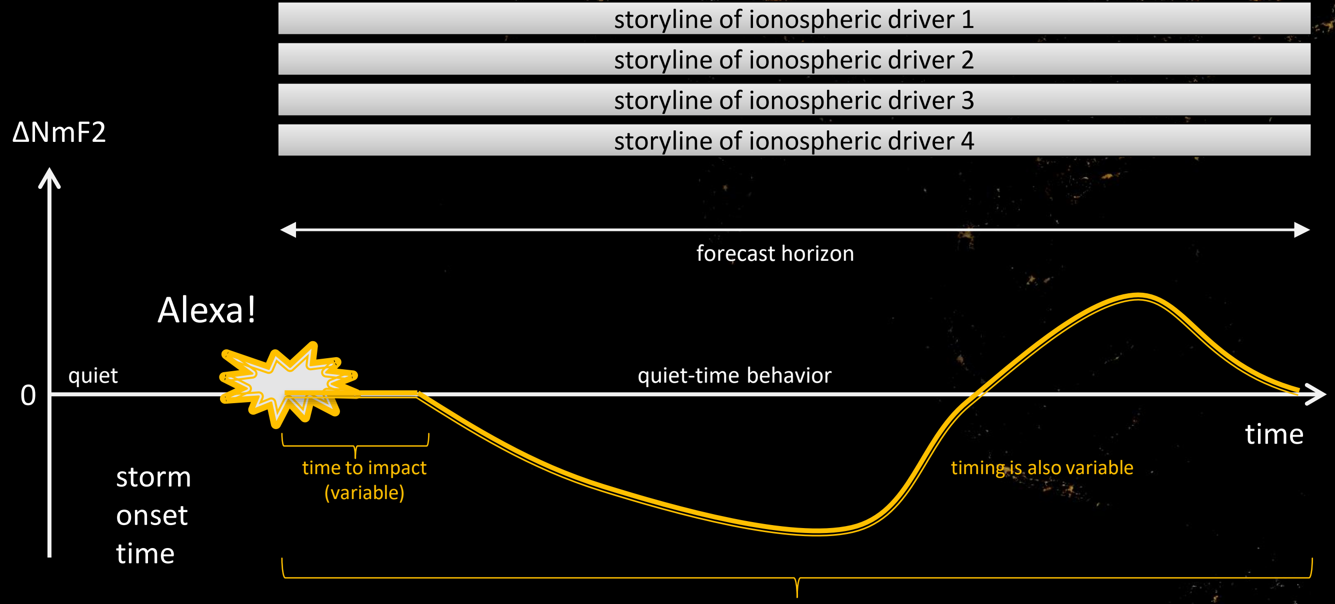


Alexa, play Yesterday by The Beatles

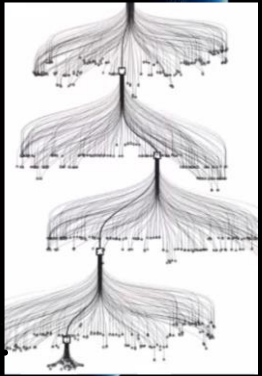
- "Yesterday" is interpreted in the context of "play"
  - Not a reference to time
  - Fetched from the database of song titles
  - The song is played to the asker
- DEEP LEARNING: multi-layered recurrent (feed-back) networ topologies
  - Support interpretation of subelements in the context of other c
  - Seems matching to the idea of interpreting ionospheric dynamics in the context of the external forces acting on it
    - Context: reports of ongoing Sun-Earth activity
    - Output: ionospheric dynamics fetched from the historical record database
    - What is different? Deep Learning of how activity processes interplay



Concept of the "Alexa" storm options



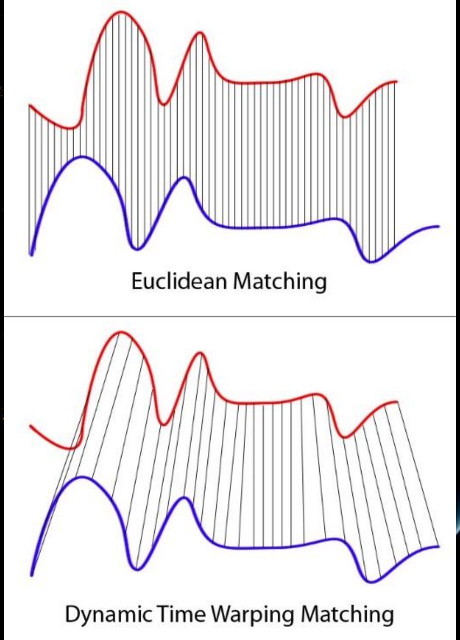
retrieved best match among stored anomaly storylines
(adjust expansion coefficients)



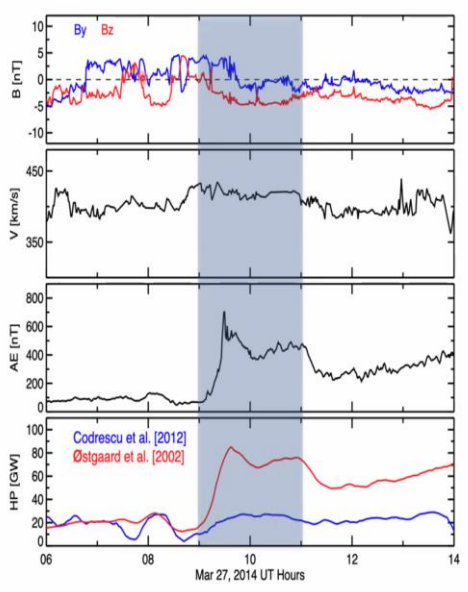
Forecast by analogy

Dynamic Time Warping (DTW)

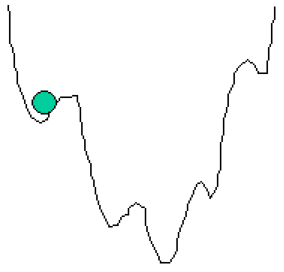
- Library-provided storm storyline of the ionosphere needs adjustment for the driver storyline
  - DTW finds a similarity between 2 storylines:
    - actual (red)
    - library (blue)
  - Assumption: driver storylines is indicative of *how different* the actual storm timing is from the library copy
  - Detected time warping is later applied to the library ΔNmF2 to correct for actual-vs-library timing



Associative memory for partial driver info



- Real-life: driver timelines are available only partially after the storm commencement
  - Associative memory for restoring the full timeline from its fragment
    - Based on the recurrent feed-back NN
    - Used for recognition of hand-written text
      - fragmentary, distorted pattern is provided
      - Memory associates the pattern with one of the [previously stored] alphabet
    - Used for image imputation
      - Partial pattern is filled using identified closest match
    - Correct shape recognition is improved with time as a greater fragment of the driver storyline become available
      - Especially, the amplitude of perturbation is relevant

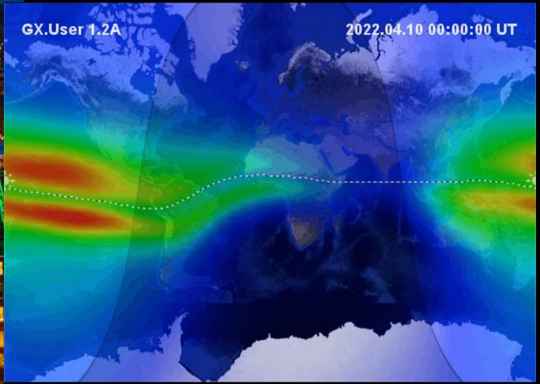


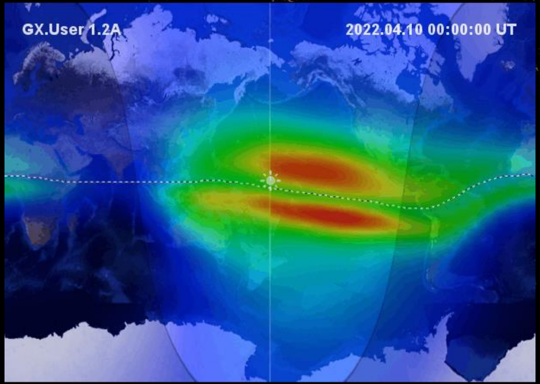
Tricks to standardize storms

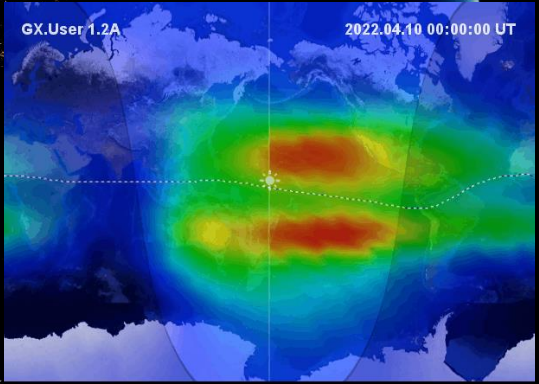
- Standard timing of library storylines with DTW upon retrieval
- Switch to local time (TBR)
  - Are anomalies corotating or LT-fixed to the Sun?
- "Demagnetization" of the library ionosphere storylines
  - Transform geomagnetic poles to geographic poles reference
    - Use modip transformation
      - Very common in modeling the ionosphere
    - Then the storyline is re-magnetized using current geomagnetic configuration
      - Using IGRF

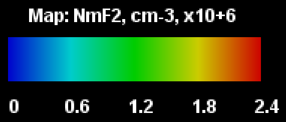
Trick: Remove Earth Rotation

mF2

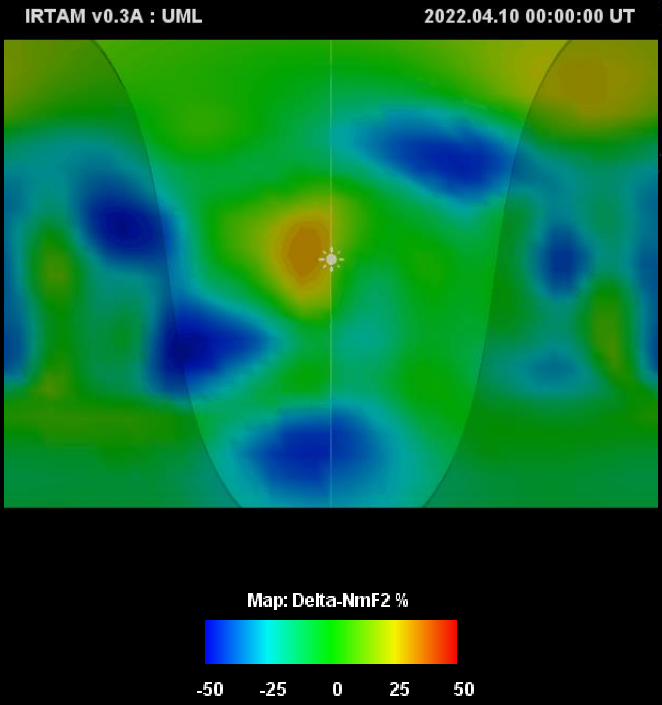




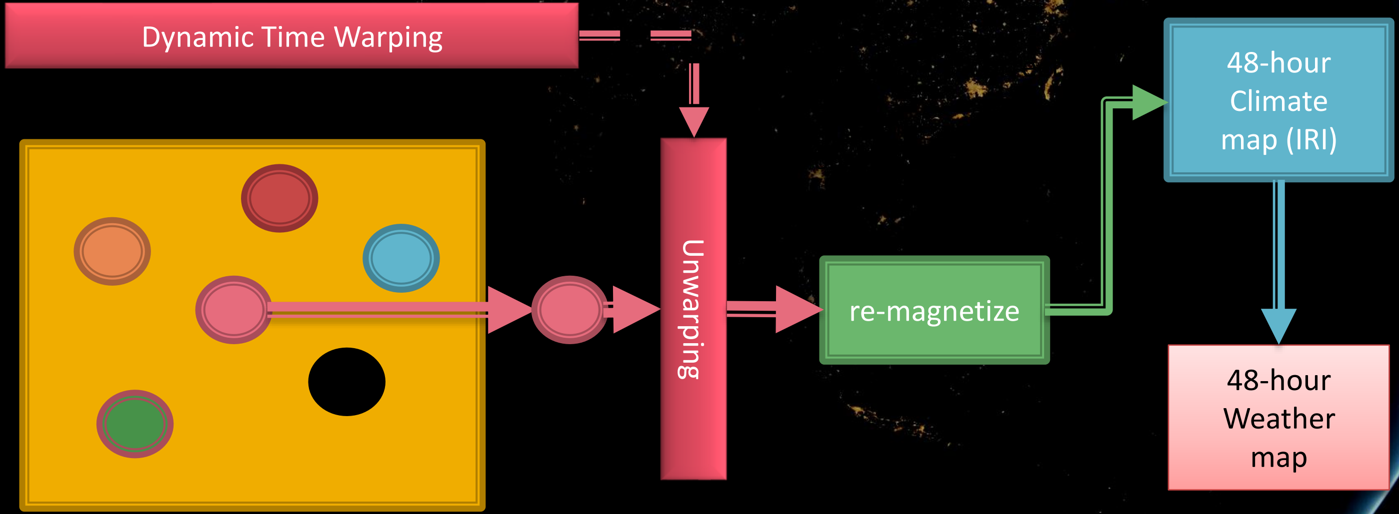




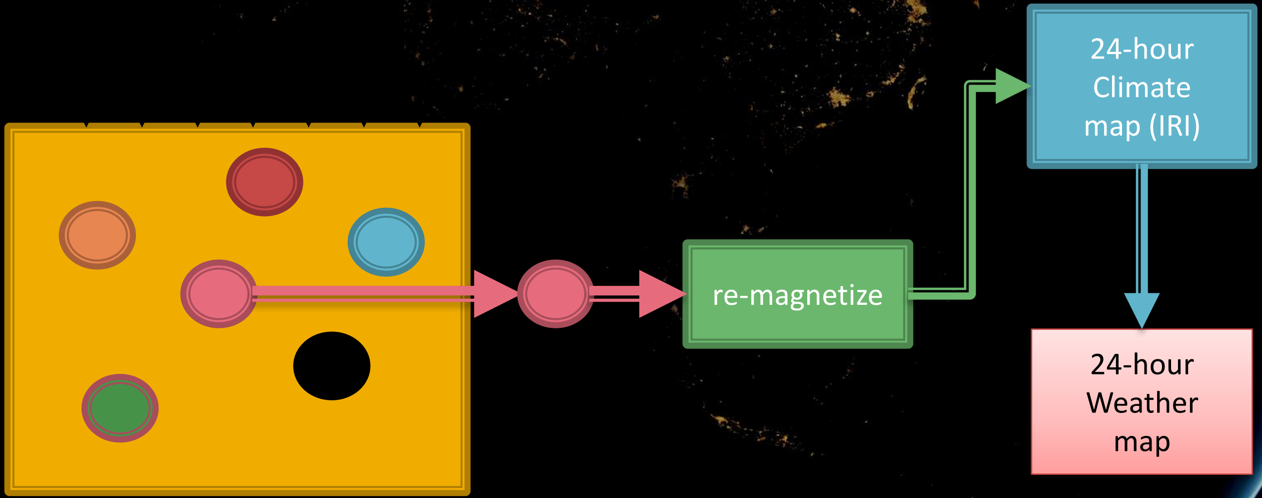
1 Day History to Store in Historical Database; this is still a grand challenge



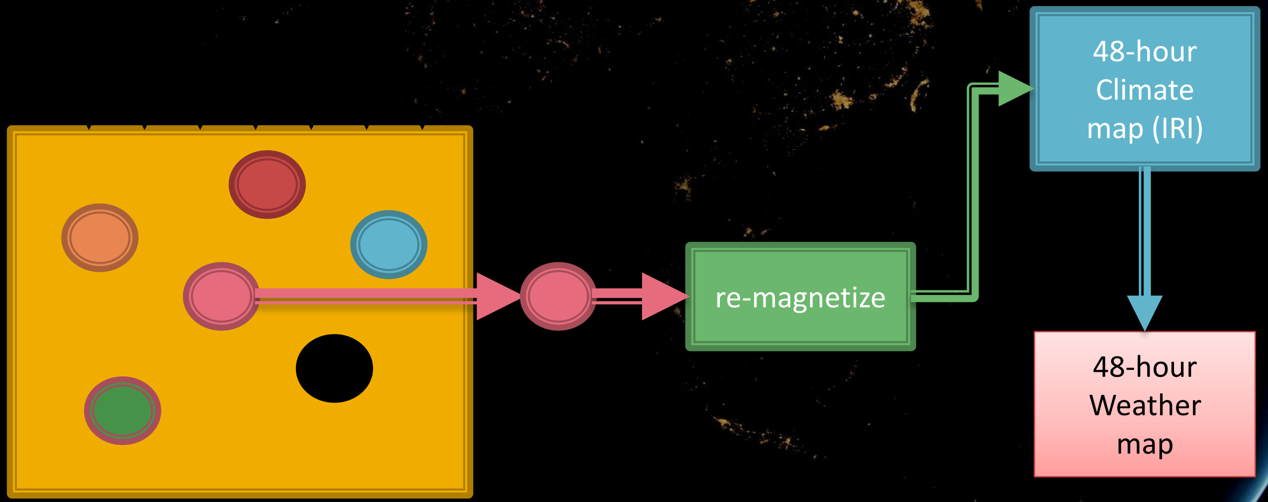
1024


Dynamic Time Warping
Unwarping
re-magnetize
48-hour Climate map (IRI)
48-hour Weather map

REALISTIC RION IONOSPHERE

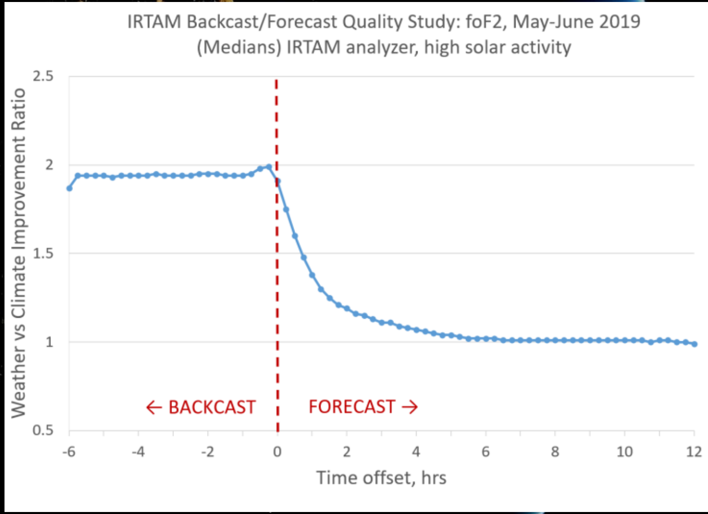


Forecasting by context-driven memory (2)



Capturing Context of Ionospheric Dynamics

- Ionosphere: immediate response to external forcing
  - Thus its current conditions do not inform future states
- Need to use timelines of all external drivers as context
  - Cannot be just one instant driver (e.g., Kp=6)
  - Driver dynamics is matched (paired) to the ionospheric storm dynamics
    - Across complete forecast timeline from onset to stop
  - Important: which driver is relevant out of the set? (Deep Learning helps; *inductive bias*)
  - Storm vocabulary:
    - capture standard storm timelines
      - not 1024 variables, but much less
    - then detect their different timing realizations
    - Natural speech example
      - The same word said slowly or quickly
      - Dynamic time warping



Natural Language Processing as DTW example

- Analogous to Sound/Syllable recognition
- Custom Language to describe storm progression