Global Ionosphere Radio Observatory

☆ Multi-nation Ionosonde Project at UMass Lowell

Ivan Galkin and GIRO Science Team

Your text here

Space Science Laboratory, University of Massachusetts Lowell, USA

UML SPACE SCIENCE LAB

IRI 2023 COSPAR CBW

May 9, 2023 ● KASI, Daejeon, South Korea

Outline

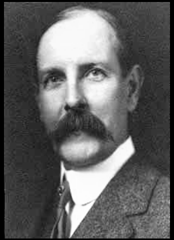
- Ionosondes and the measurements they take
- Realistic Ionosphere (RION)
  - Databases and services
    - Incl. DIDBase, GAMBIT, TID Explorer, and RayTRIX
- Real-time IRI Task Force: weather nowcast and forecast
- AI for IRI

Ionosonde Pre-history

Guglielmo Marconi

Cross-Atlantic wireless communications via ionosphere (1901)

Nobel Prize: 1909



Oliver Heaviside and Arthur Edwin Kennelly

Announced existence of ionosphere to explain Marconi's result (1902)

Sir Edward Victor Appleton

Discovered Kennelly-Heaviside layer (1920), labeled it 'E'

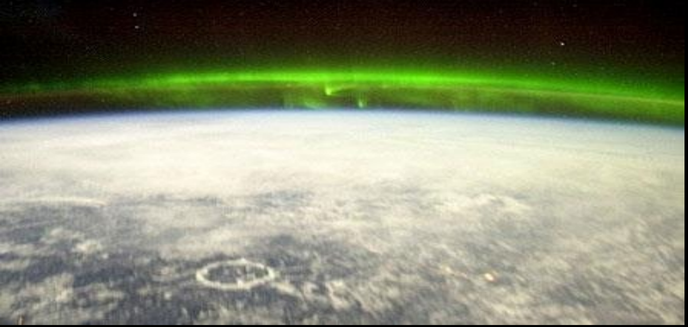
Discovered two more layers above and below E, labeled 'F' and 'D' (1926).

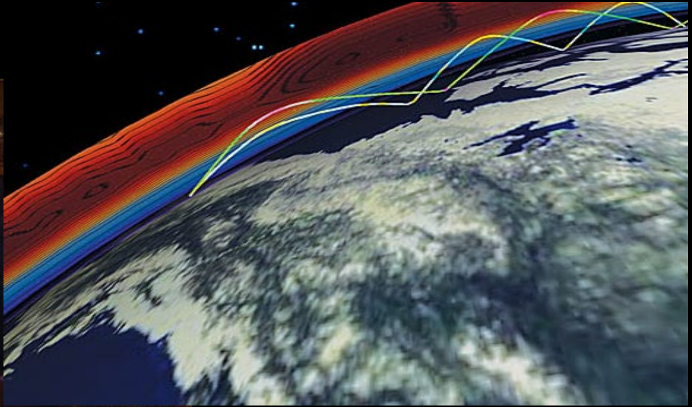
Refused relabeling them to 'A', 'B', and 'C'.

Nobel Prize: 1947

Ionosonde: Quest for the Mirror Altitude

Part of ionosphere lighted by precipitating particles





- 1925
  - Cavendish Lab, Cambridge, UK
    - Appleton and Barnett
    - Chirp sounding
  - Carnegie Institute of Washington, USA
    - Brett and Tuve
    - Pulsed sounding, 1 ms, 2 frequencies
- 1930s
  - Outburst of HF devices probing higher altitudes in the ionosphere
    - 6 people needed to operate one
  - 1931, Jan 11: Slough Observatory, UK: first 24-hour sequence of monitoring critical frequency
  - 1934: HF Broadcasting era

First Ionogram, 1933

- Answer to demand of continuous MUF monitoring for HF broadcasting stations
  - Maximum Usable Frequency
  - Much like terrestrial weather service
- New technologies by Theodore Gililand, USA
  - Colocated Tx and Rx
  - Recording device!

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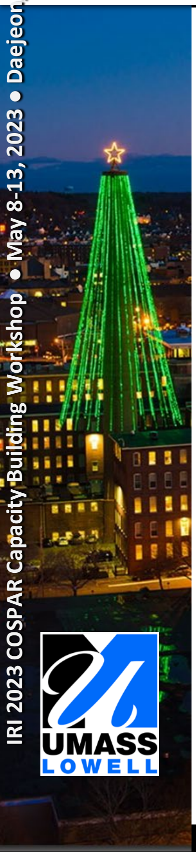
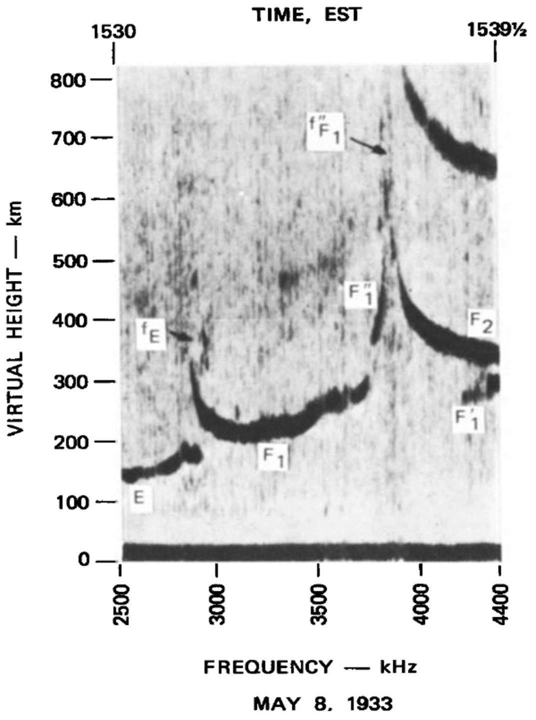
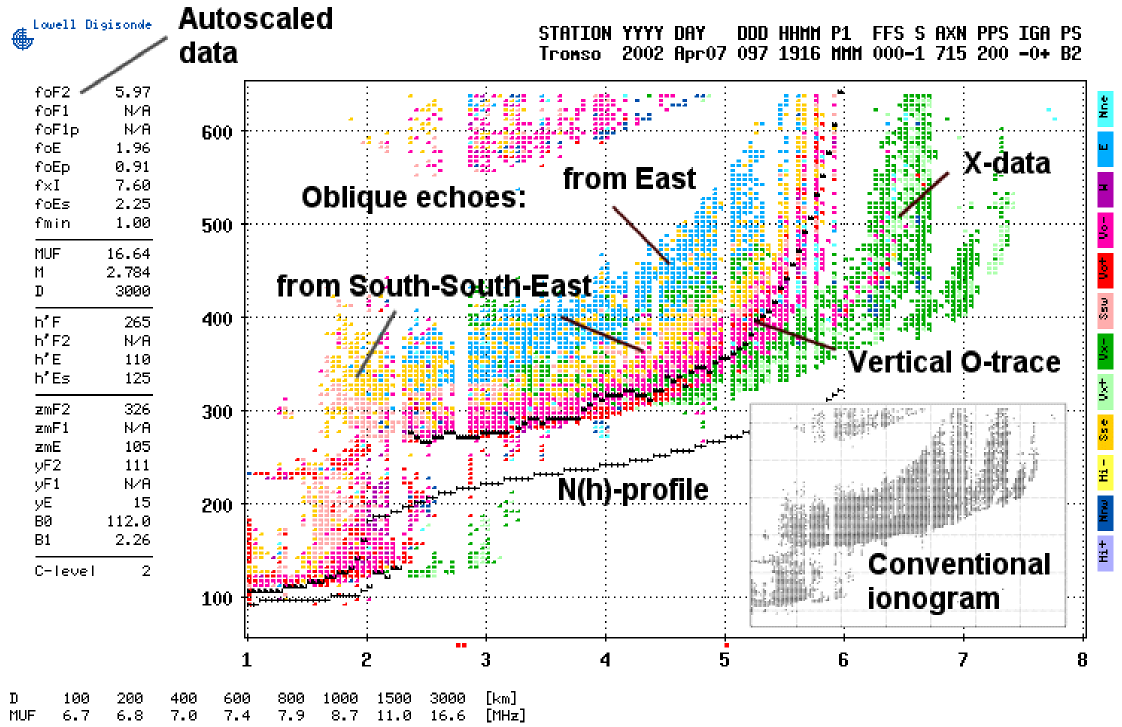
Ionogram in 1933 and nowadays



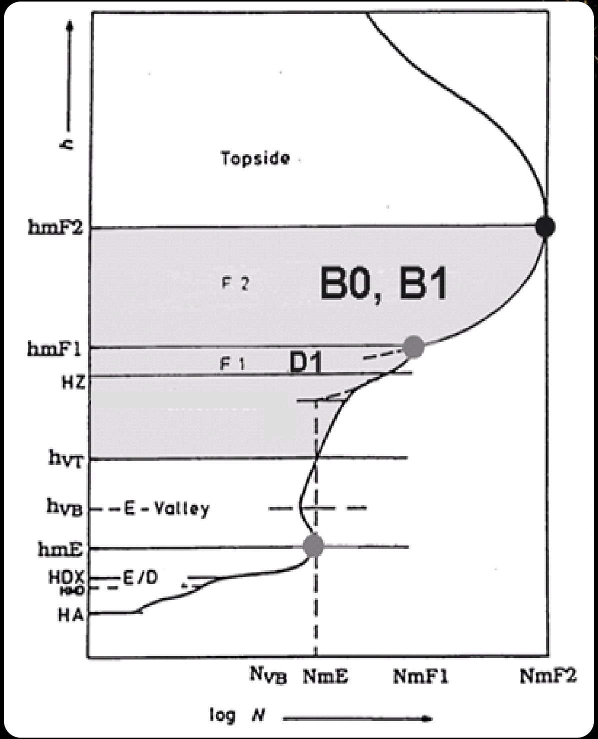




Ionogram-derived characteristics

- URSI Standard List ©1989
  - ~80 different kinds of ionogram-derived values
    - N_mF2, hmF2, foEb, … …
  - ARTIST has ~ 48 of these
    - Analysis time per ionogram?
      - Manual analysis is not realistic anymore… too expensive
      - Why? Who cares? New science after 100 yrs of research?
        - The right question is "which ones are especially important"?

Most important chars: IRI



- N_mF2, h_mF2, *B0*, *B1*
- N_mF1, h_mF1, *D1*
- Interim layer: H_z
- Valley: h_{vt}, N_{vb}
- N_mE, h_mE, H_{DX}
- N_mD, h_mD, H_a
- No topside spec possible

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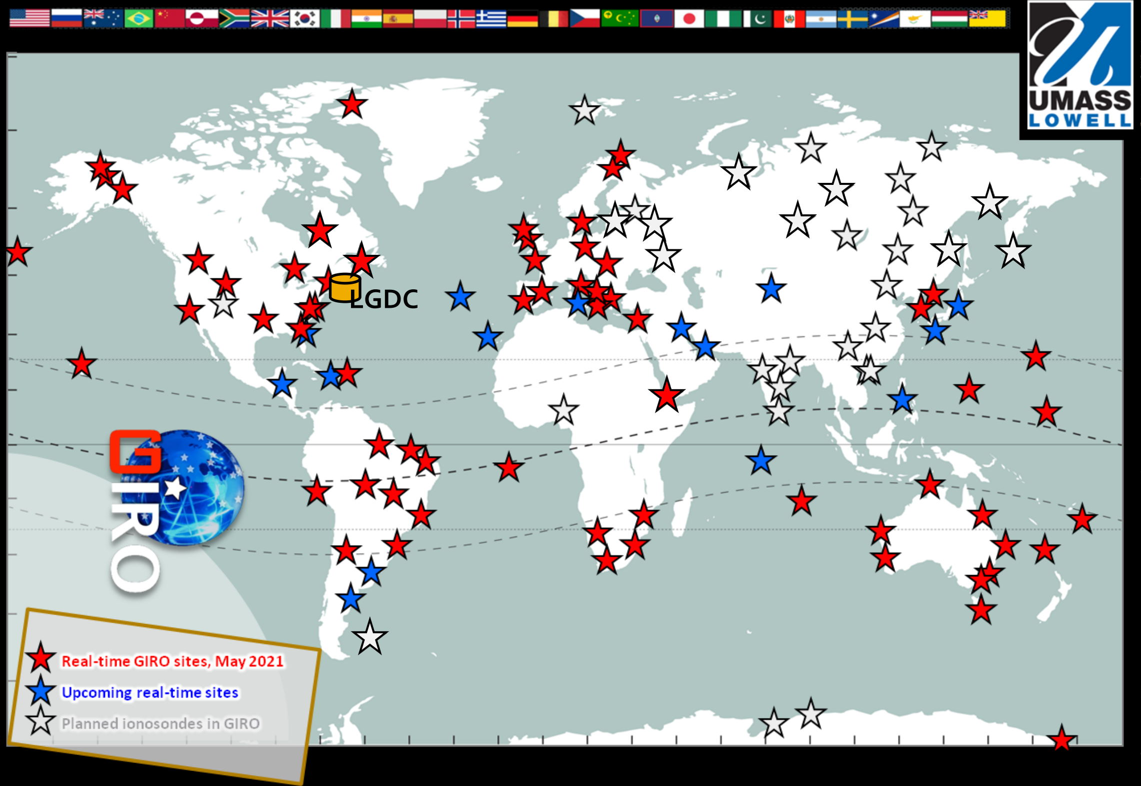
Ionospheric Weather Capability

- Accurate Global Prompt Nowcast and Forecast
  - Near-real-time data are in demand
  - Ionosphere has a short memory
    - Measurements 1 hour old are 50% useful in nowcast
    - Measurements 4 hours old are not useful
  - Global sensor networks with continuous data streams at <1 hr latency?
    - Space-borne ionosphere observing fleet… not quite ready
    - Ground-based network
      - GNSS "Ultra-rapid" and nRT networks, ~300 receivers
      - …and then there are HF ionosondes and GIRO

GIRO: real-time streaming



- Real time
- BY NC SA academic use
- Standard URSI chars is just a beginning…

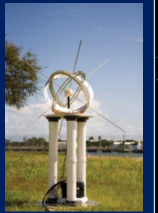
Modern Apps Impacted by Ionosphere

GNSS PPP / RTK

- **Affected systems: autonomous vehicles and machinery**
- **TID as a *Silent Accuracy Killer***

- **Worse than the loss of lock and scintillation**
  - **(Hard to detect)**

HF Geo



- **Geolocation of uncooperative HF transmitters**
- **Tens of km positioning errors**
- ***Short-range catastrophe* during TID passages**

Traveling Ionospheric Distrubance

Managing HF Communications

- **High-reliability low-latency messaging/voice**
  - **Instant business transactions**
  - **Rescue/covert missions, soldier-to-headquarters comms**
  - **Dispatcher-to-pilot safety messages, esp on transpolar flights**
  - **HAM radio enthusiasts**

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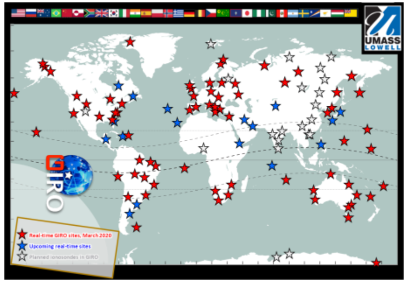
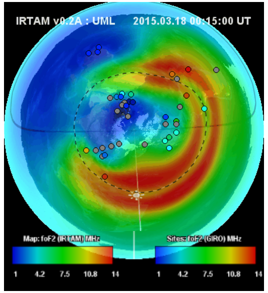
UML Realistic Ionosphere

RION



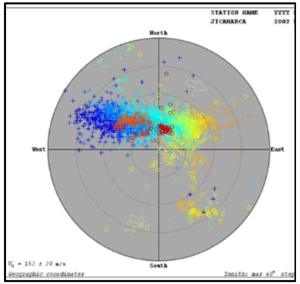
GIRO

Measurements



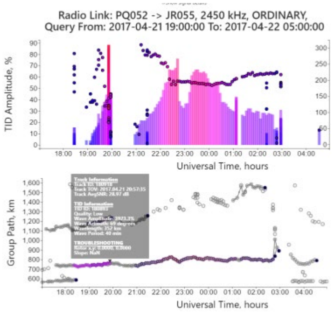
IRTAM 3D

Global Model



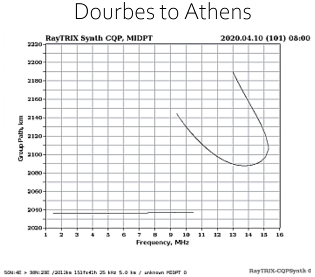
SkyLITE

Plasma Drifts



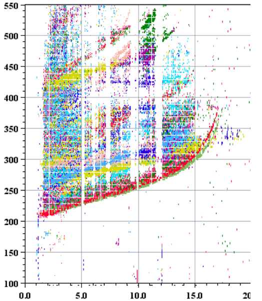
TID Explorer

TID Warnings



RayTRIX

Raytracing



IDI

Disturbance Indicator +Es

United Nations International Space Weather Initiative

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Take home: GIRO Web Portal


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

GLOBAL IONOSPHERE RADIO OBSERVATORY

with Real-Time & Retrospective HF Ionospheric Sounding Data from Lowell DIDBase

The Lowell GIRO Data Center (LGDC) implements a suite of technologies for post-processing, modeling, analysis, and dissemination of the acquired and derived data products:

IRTAM
IRI-based Real-time Assimilative Model, "IRTAM", that builds and publishes every 15-minutes an updated "global weather" map of the peak density and height in the ionosphere, as well as a map of deviations from the classic IRI climate;

GAMBIT
Global Assimilative Model of Bottomside Ionosphere Timelines (GAMBIT) Database and Explorer holding 15 years worth of IRTAM computed maps at 15 minute cadence;.

Ionograms
17+ million ionograms and matching ionogram-derived records of URSI-standard ionospheric characteristics and vertical profiles of electron density;

Doppler Skymaps
10+ million records of the Doppler Skymaps showing spatial distributions over the GIRO locations and plasma drifts;

TID
Data and software for Traveling Ionospheric Disturbance (TID) diagnostics

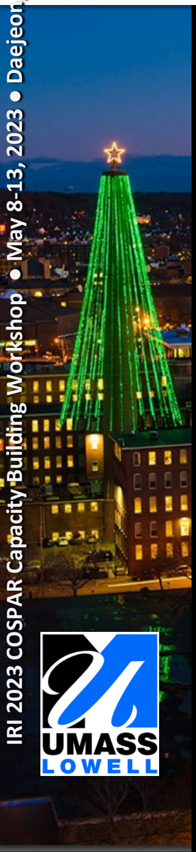
HR2006
HR2006 ray tracing software mated to the "realistic" IRTAM ionosphere.

ALL OPERATING AND UPCOMING GIRO SITES:

Current and prospective sites with inputs to assimilative models

In cooperation with the URSI Ionosonde Network Advisory Group (INAG), the LGDC promotes cooperative agreements with the ionosonde observatories of the world to accept and process real-time data of HF radio monitoring of the ionosphere, and to promote a variety of investigations that benefit from the global-scale, prompt, detailed, and accurate descriptions of the ionospheric variability.

- https://giro.uml.edu
- Access to all GIRO resources
- Some real-time data are "public"
  - CC BY NC SA
    - non-commercial use
    - need to credit providers
    - share-alike

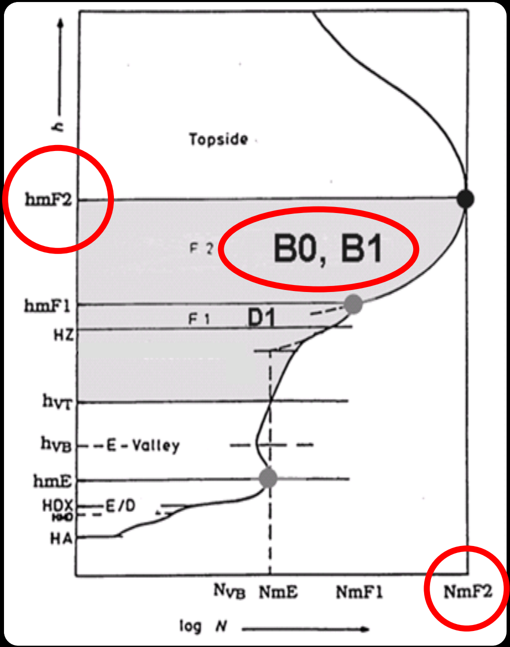


Demo of GIRO Web Portal

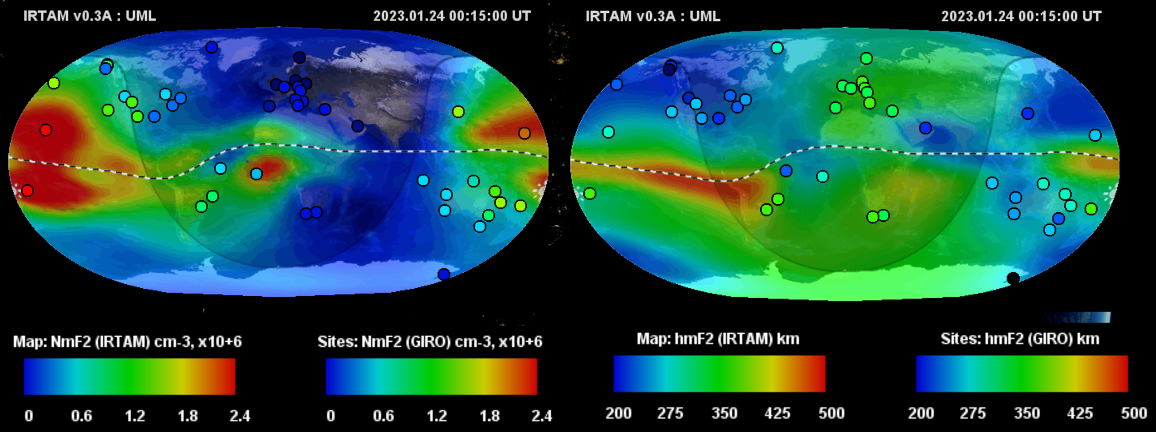
IRTAM 3D

IRI-based Real-Time Assimilative Model

IRTAM 3D: Four out of 16



1D vertical profile of plasma density



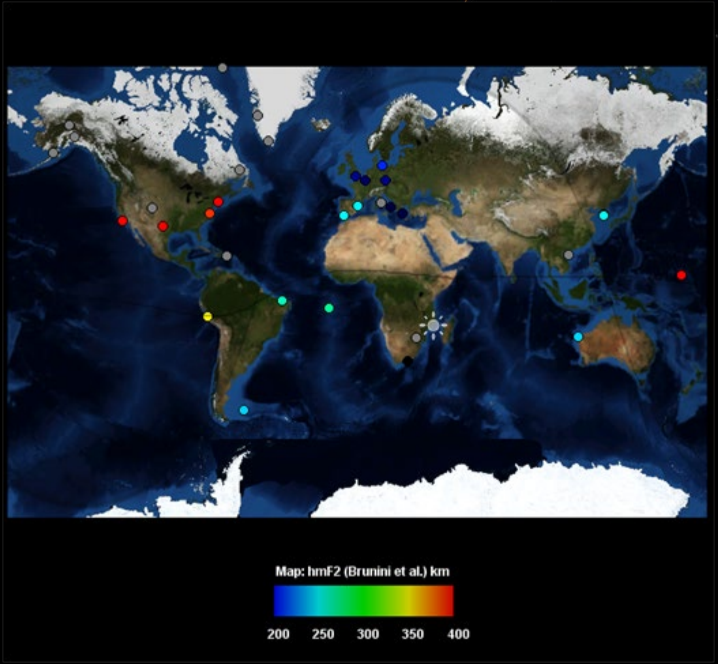
N_mF2 h_mF2

One day of ionospheric dynamics

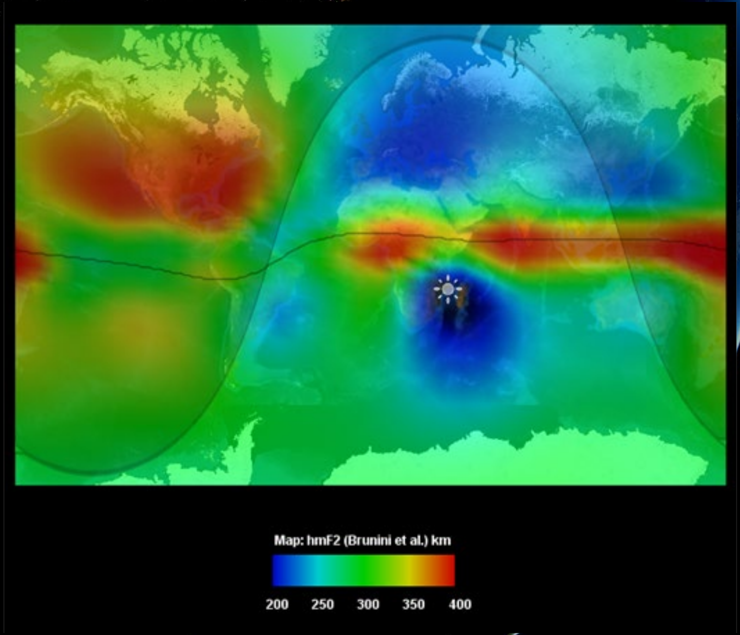
"Ionosphere is a major operational nuisance" © USAF

Modeling based on fragmentary data

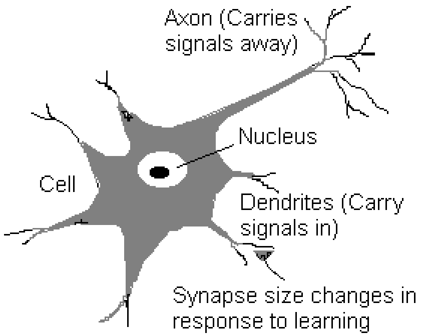
Ionosonde Network Real-Time hmF2



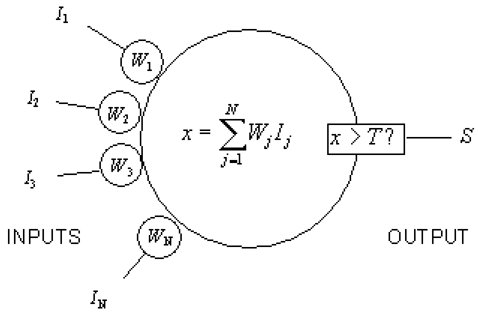
Global hmF2 Weather



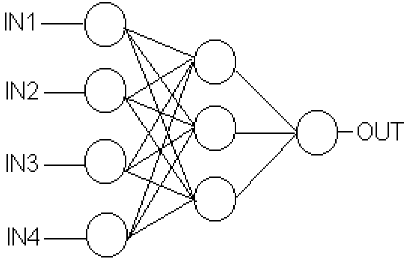
Neural Doctrine: Galloping Introduction



Natural Neuron

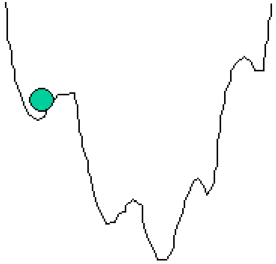


Artificial Neuron
(classic spin)
(mean-field also available)



Neural Network

$$E(\vec{S}) = -\frac{1}{2}\sum_{i=1}^{N}\sum_{j=0, j\neq i}^{N} W_{ij} S_i S_j$$

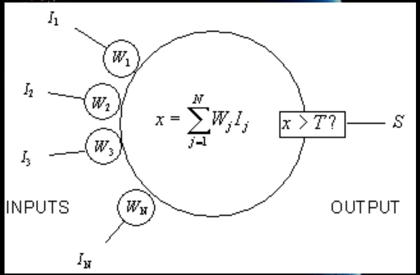


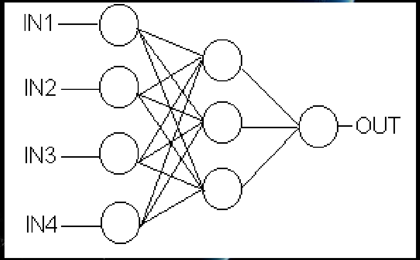
Energy Function
of Neural Dynamics

The roaring 1990s: an outburst of algorithmic NNs to replicate human intelligence

Historical Average © Feed-forward NN

- Training phase
  - present NN with known examples (input and output) for training
    - determining the W_{ij} weights – back-propagation method
- Execution phase
  - WHAT-IF: present trained NN with previously unknown inputs to obtain a predicted output
  - Superior inductive bias of NNs: the capability of gleaning the nature of the system in order to do good WHAT-IFs.
  - Superior but little understood
    - Black-Box: No clue how and why it works well
    - Caused a severe AI Winter in the 2000s
      - NSF would not fund NN projects
      - Physics journals would not publish NN model results
    - White box and Gray box
- All feed-forward NN architectures are in "historical analogies" category
  - Subject to *AI Winter*





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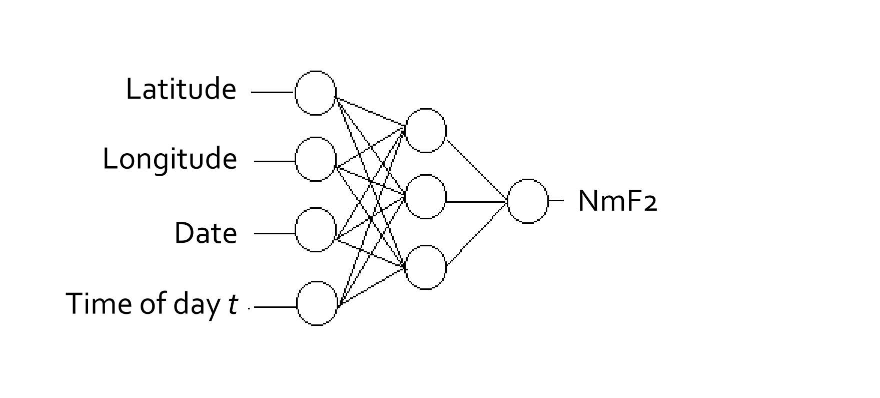
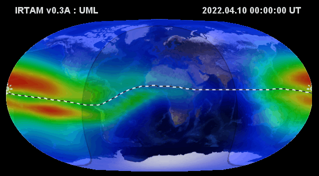
Feed-forward NN for quiet-time ionosphere

QUIET-TIME PREDICTION NN MODEL



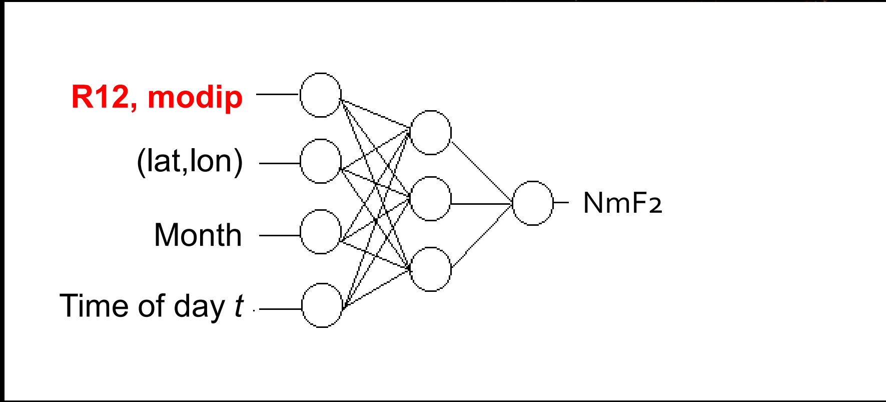
Research funding agencies:
no-no, this is a SNAKE OIL



- Train a NN to predict peak density in the ionosphere N_mF2, as a function of:
  - Time of day
  - Date (year, day of year)
  - Location (lat, lon)
- WHAT-IF: run for different dates, times, and locations

Feed-forward NN for quiet-time ionosphere

QUIET-TIME PREDICTION NN MODEL



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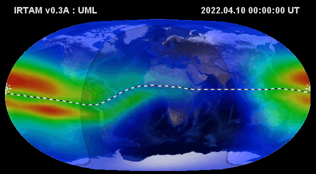
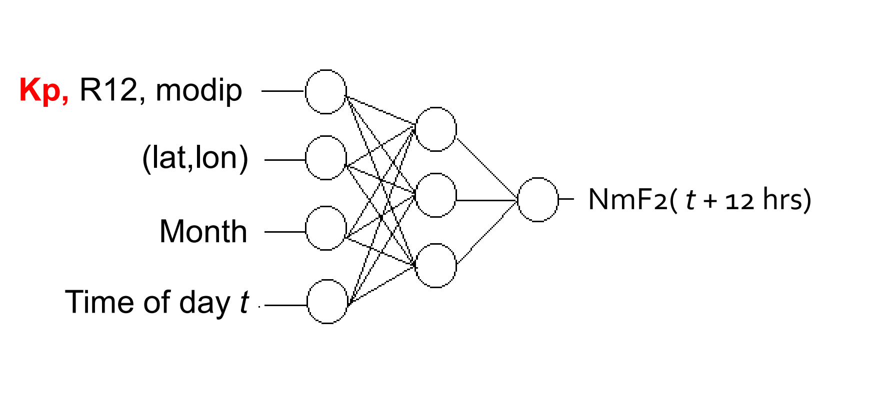


- Train a NN to predict quiet-time peak density in the ionosphere N_mF2 12 hours ahead, as a function of:
  - Time of day
  - Month
  - Location (lat, lon)
  - Sunspot number
  - Modip
- WHAT-IF: run for different dates, times, locations, R12, modips

Feed-forward NN for forecasting ionosphere

FORECASTING NN MODEL FOR 12 HOURS AHEAD



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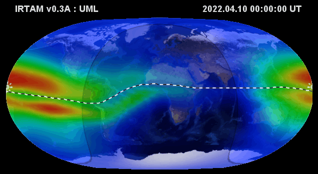


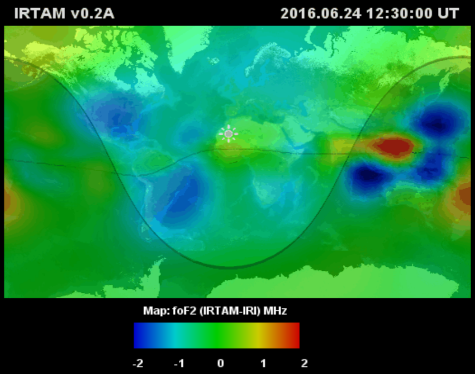
- Train a NN to predict peak density in the ionosphere N_mF2 12 hours ahead, as a function of:
  - Time of day
  - Date (year, day of year)
  - Location (lat, lon)
  - Geomag index Kp
- WHAT-IF: run for different Kp values, dates, times, and locations

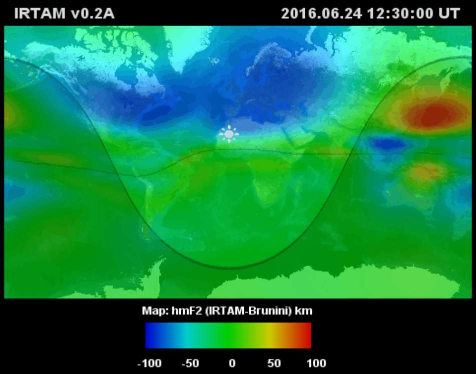
Use *Deviation* from IRI

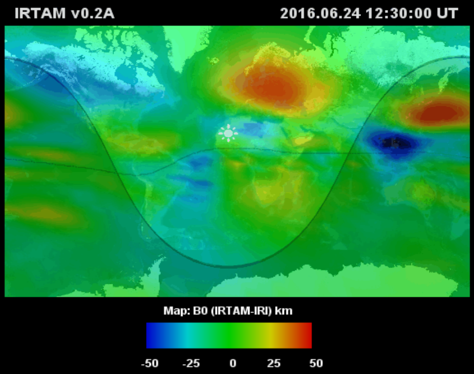
- Analysis of Weather *anomalies* observed at the sensor sites to smoothly transform the underlying IRI (*morphing*)
  - This is the IRTAM principle
  - NO NEED to capture the geophysics of sun activity, modip migration, seasonal specifics – IRI does it for you
  - Just morph IRI into agreement with observations
- Classic GRAY BOX approach

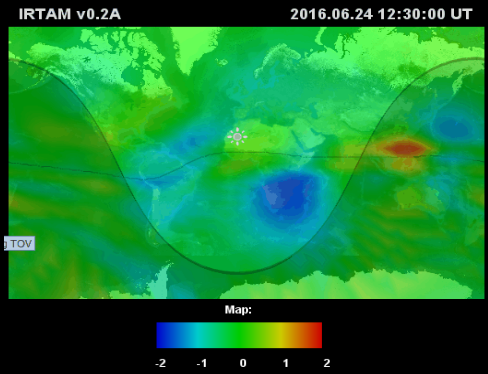
Anomaly Maps (IRTAM-minus-IRI)

HOW IONOSPHERE IS DIFFERENT FROM ITS QUIET-TIME STATE







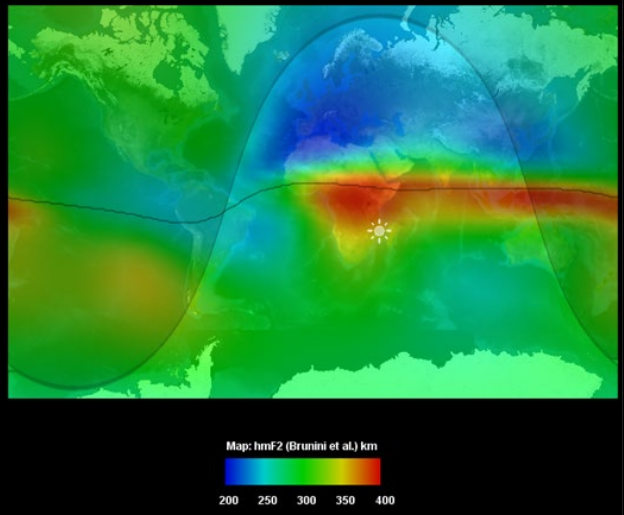


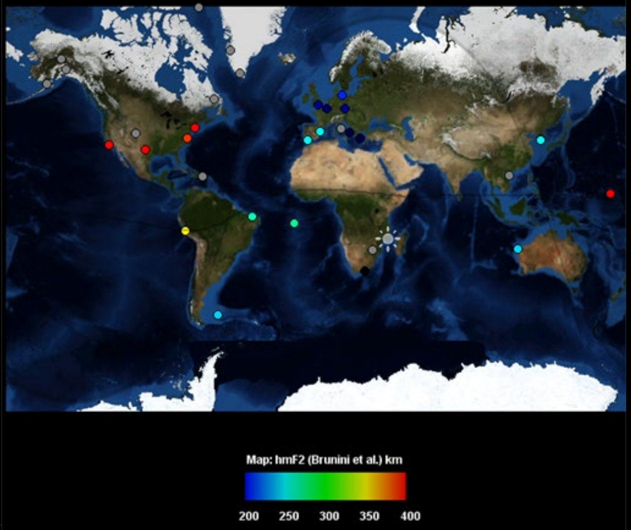
$\Delta f_o F2$ $\Delta h_m F2$ $\Delta B0$ $\Delta B1$

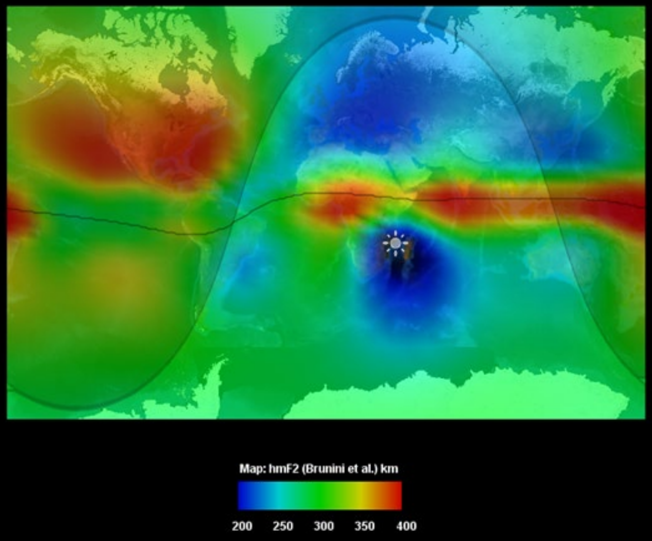
NECTAR Algorithm

NECTAR

Global hmF2 "Climatology" IRI	Ionosonde Network Real-Time hmF2	Global hmF2 Weather



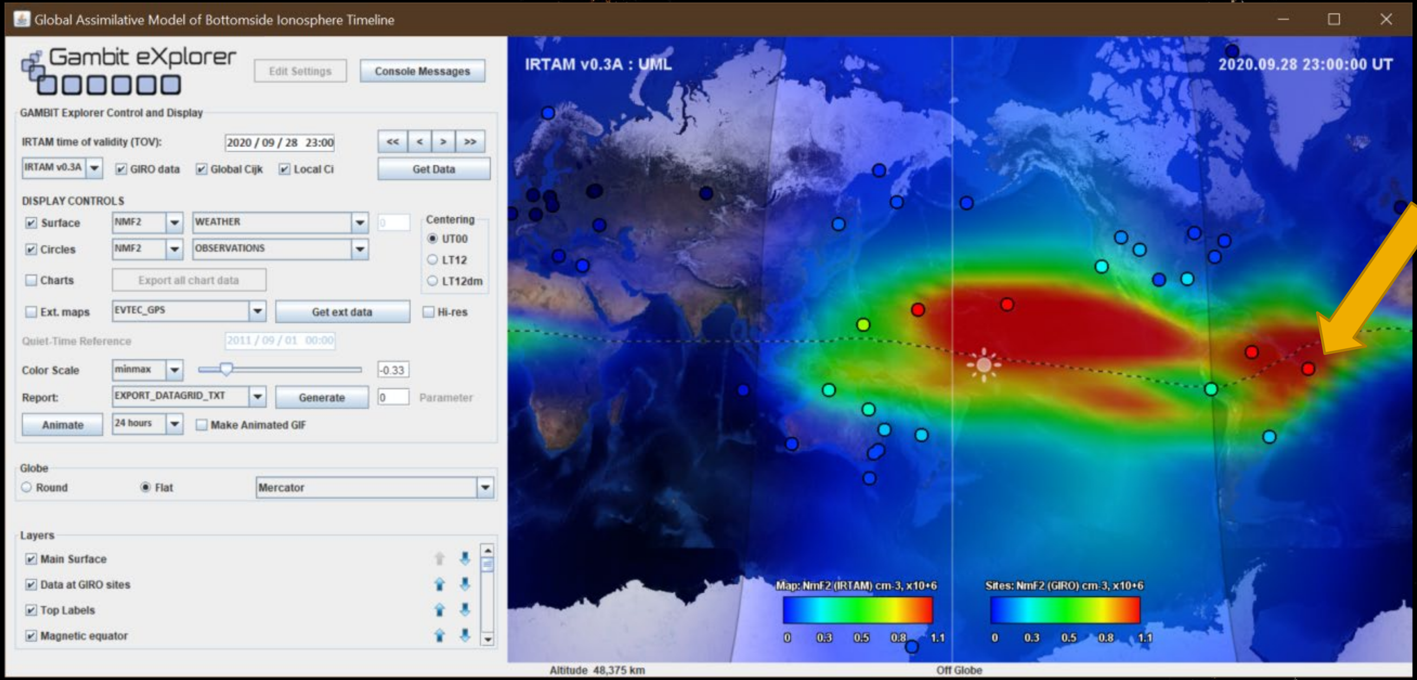




Free for academic use: GAMBIT Explorer UserApp 1.0A
Download from https://giro.uml.edu/GAMBIT/

GAMBIT EXPLORER

ACCESS TO IRTAM DATA

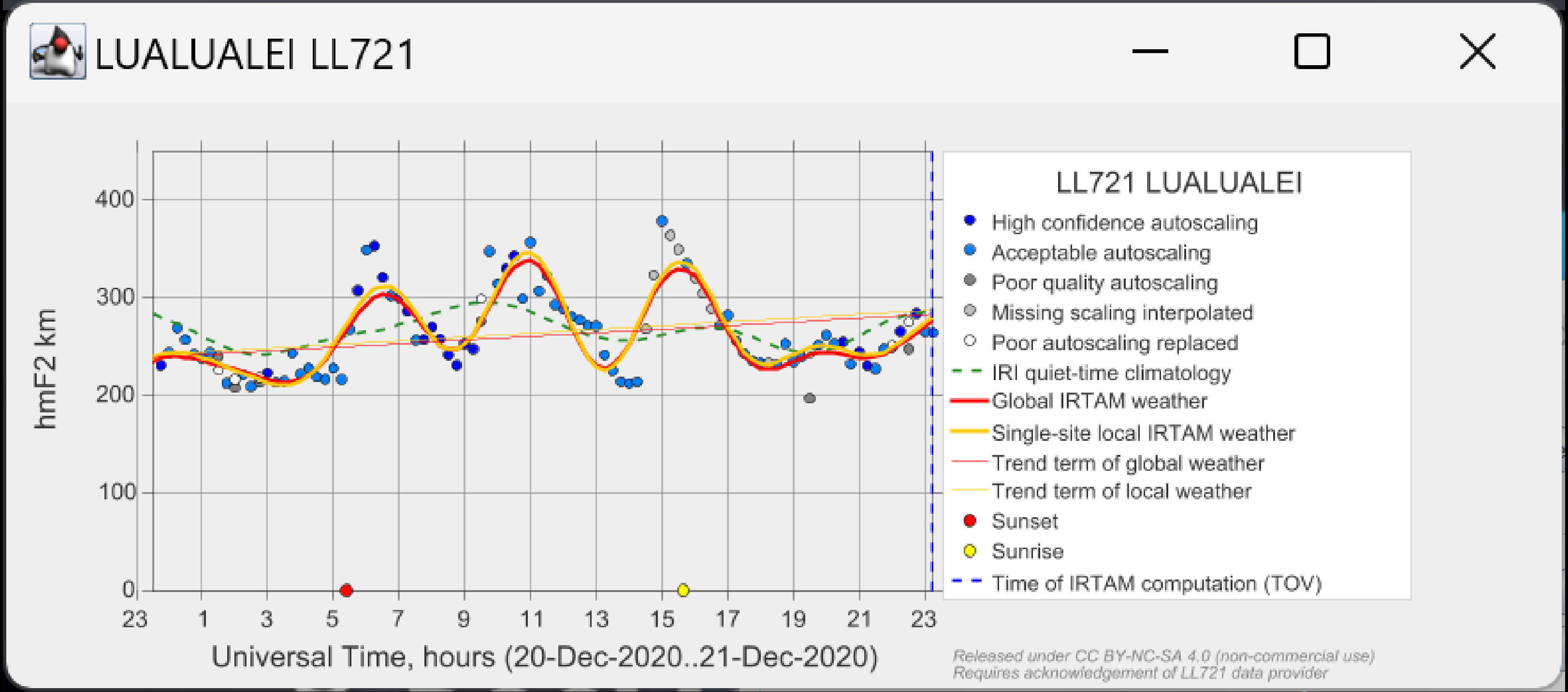


CLICK FOR DETAILS

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

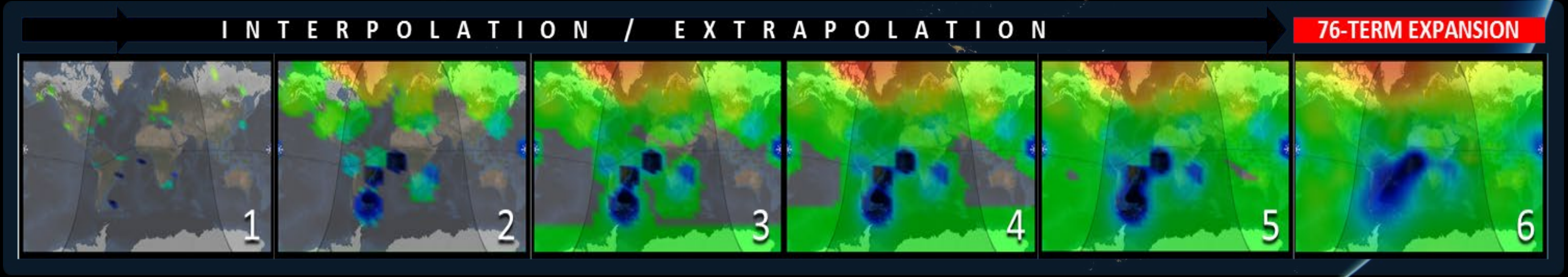
One station in GAMBIT X

One IRTAM Computation = Red Line, matches 24 hours of data



IRTAM is a 4DDA system

- 3DDA = assimilation of the latest data
- 4DDA = previous data history is analyzed at the update step of assimilation
- IRTAM = 4DDA with 24-hour history analysis
  - Looks at 24-hour *deviations* from IRI, ΔP
  - Computes diurnal harmonics of ΔP
  - Each harmonic *i* is analyzed separately during the spatial expansion of ΔP_i

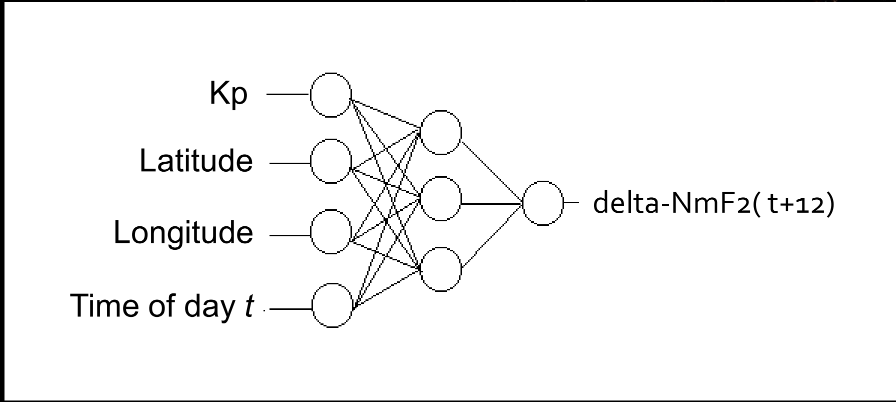


GAMBIT Explorer

- GAMBIT = Global Assimilative Modeling of Bottomside Ionosphere with Topside extension
  - Includes access to 23 years of IRTAM computations
  - Includes access to MIT Madrigal VTEC collection
  - Uses data fusion of GIRO and GNSS capabilities to reason about "effective slab thickness" of the ionosphere
    - Certain views of topside ionosphere using only ground-based sensor systems
      - Low latence real-time applications of space weather
- Available for download at https://giro.uml.edu/GAMBIT

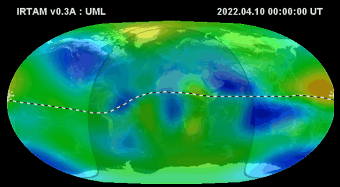
Feed-forward NN for *forecasting* ionosphere

FORECASTING NN MODEL FOR 12 HOURS AHEAD



- Train a NN to predict *deviation* of N_mF2 from the expected quiet-time behavior 12 hours ahead, as a function of:
  - Time of day
  - Location (lat, lon)
  - Geomag index Kp
- Run it for different Kp values and locations (what-if)
  - Obtain 2D map of ΔNmF2
  - Apply Δ to quiet-time predicted 2D map of NmF2

Research funding agencies: this is a GRAY BOX, but probably will not be convinced

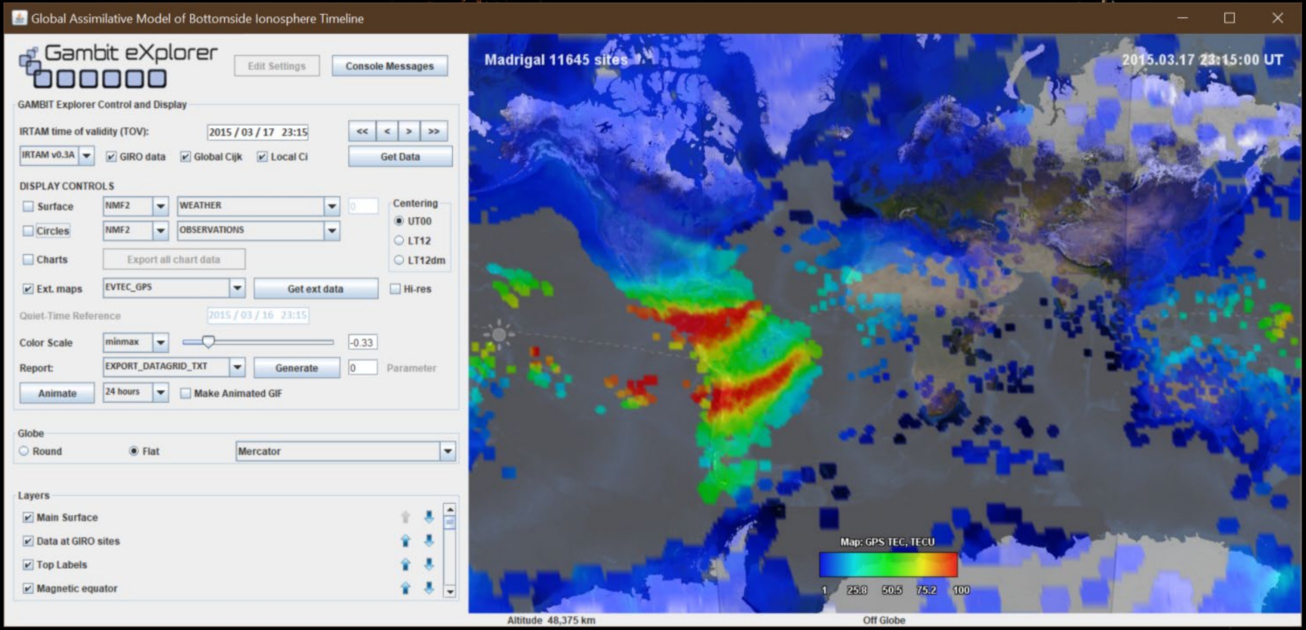


GNSS and GIRO Data Fusion

Global real-time VTEC and NmF2 for slab thickness evaluation

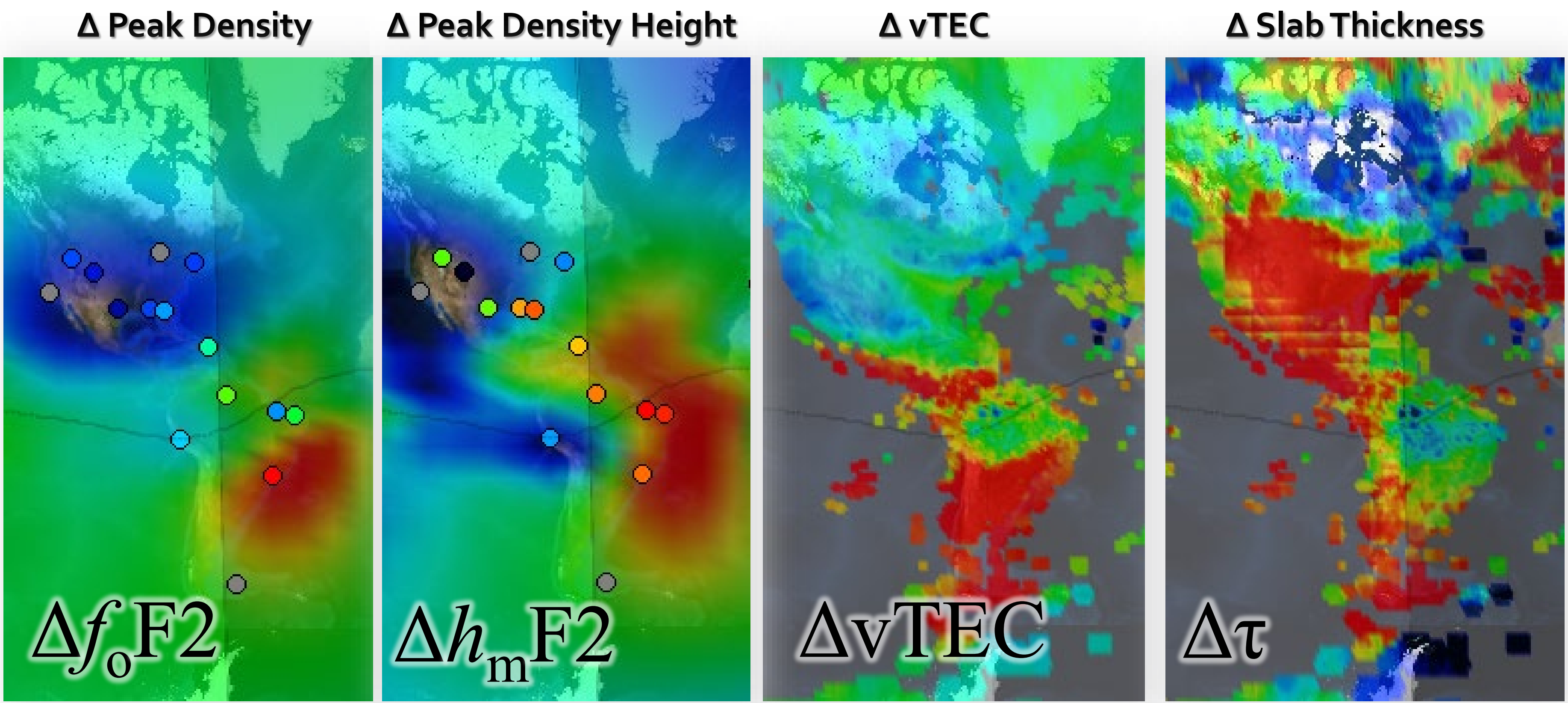
VTEC Availability in GAMBIT-X

VTEC data courtesy MIT Madrigal, Anthea Coster



- GAMBIT Explorer has connection to Madrigal database of VTEC

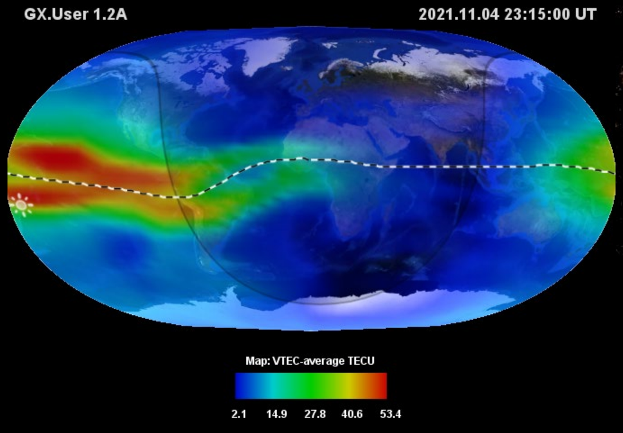
IRTAM paired with GNSS TEC



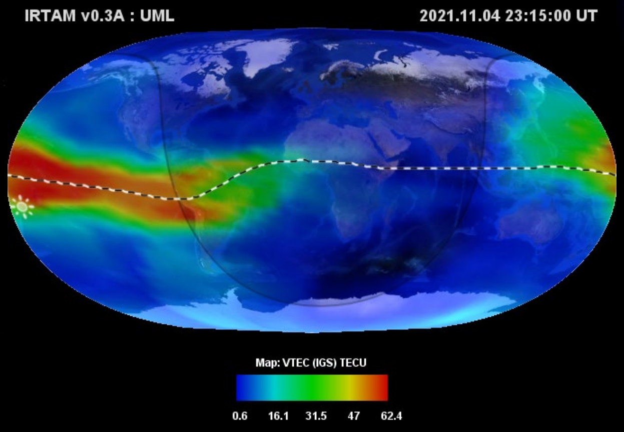
VTEC data courtesy Anthea Coster, MIT Madrigal

Other VTEC data in GAMBIT-X

VTEC data courtesy IGS Center in Olsztyn, University of Warmia and Mazury, Poland



30-day Average VTEC

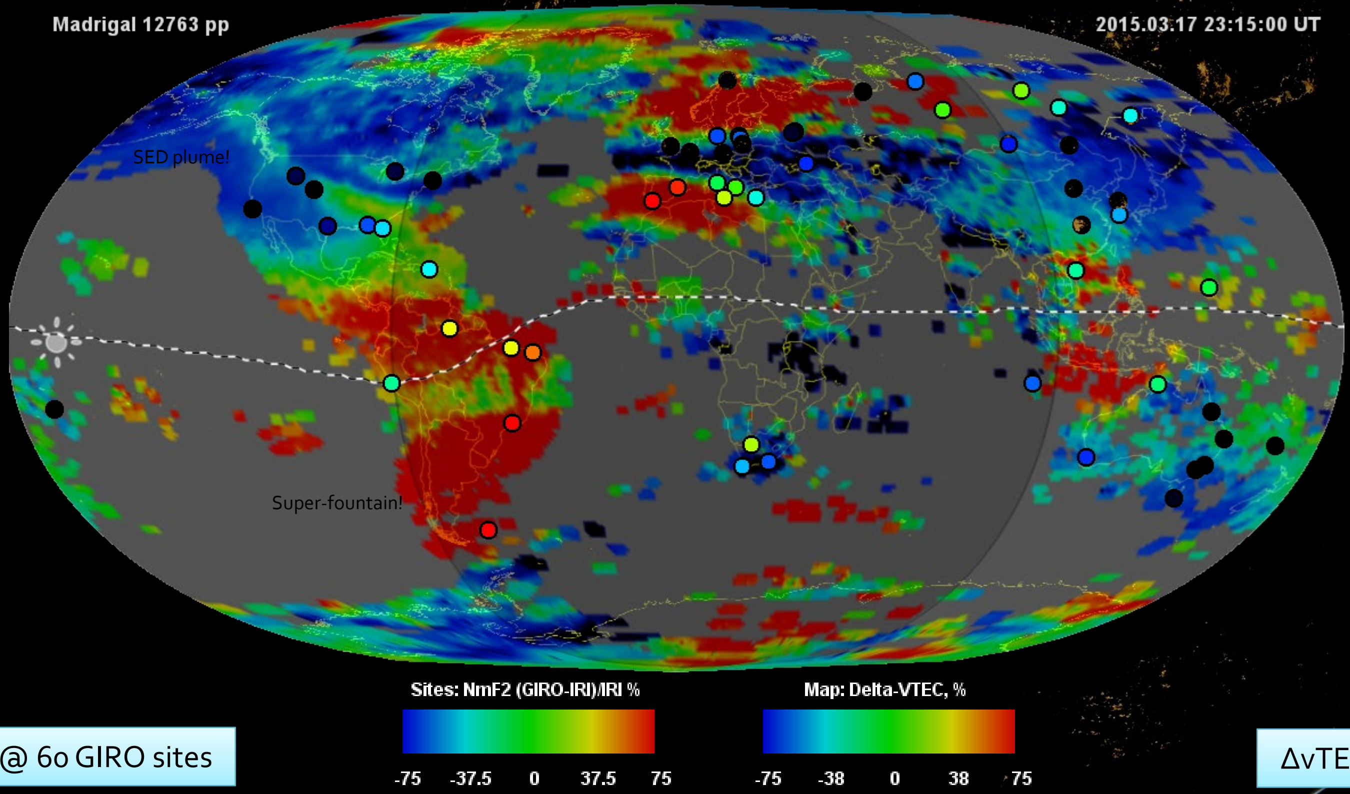


Real-Time VTEC
very very soon

- GAMBIT Explorer has connection to Olsztyn server

Superimposed ΔVTEC and ΔNmF2

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



Gambit eXplorer

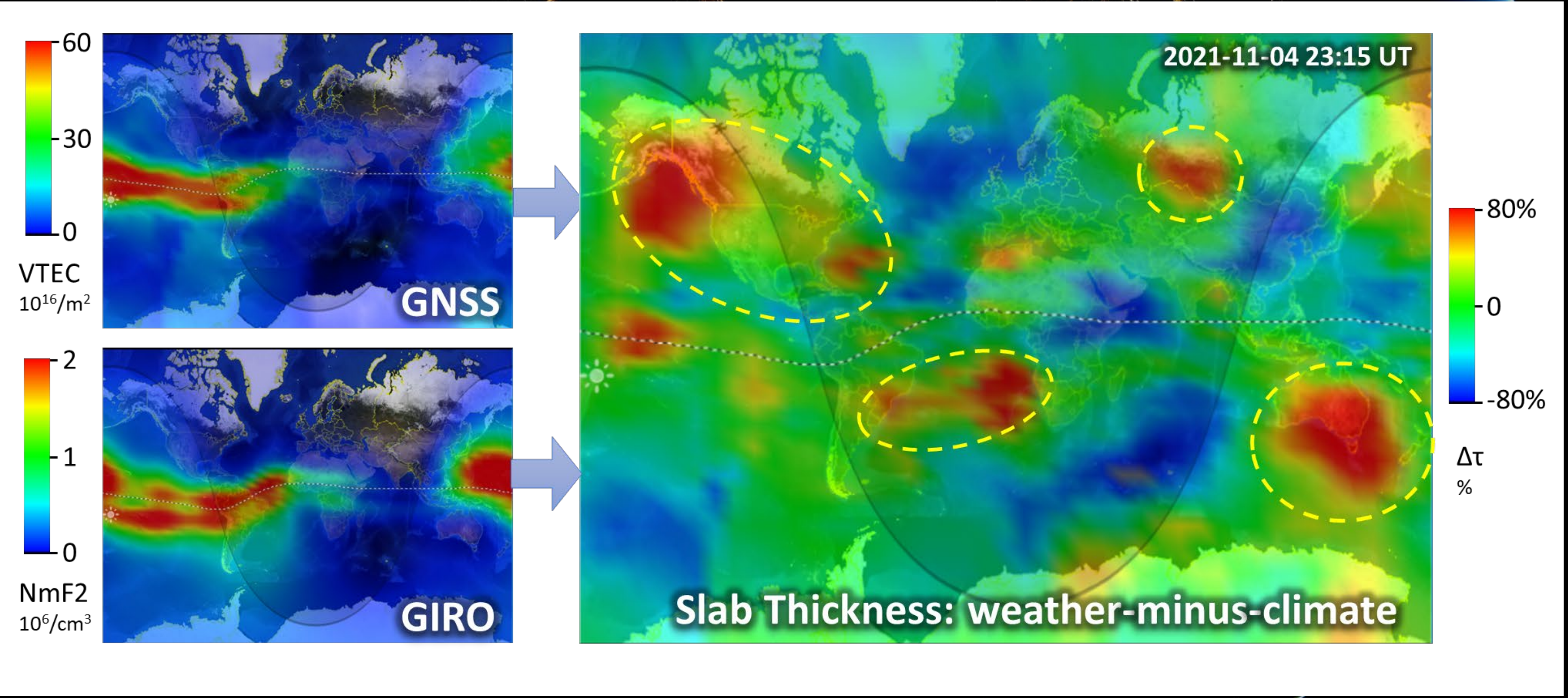
giro.uml.edu/GAMBIT

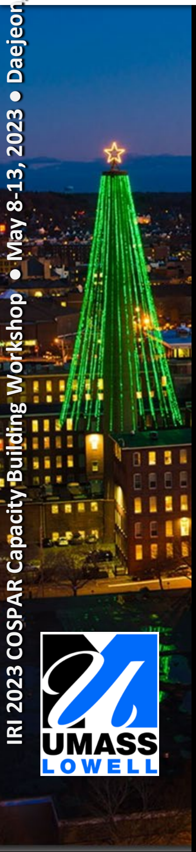
ΔNmF2 @ 60 GIRO sites

ΔvTEC @ 6342 GNSS sites

Slab Thickness Anomaly Map

GNSS GIM data in near real-time, soon!





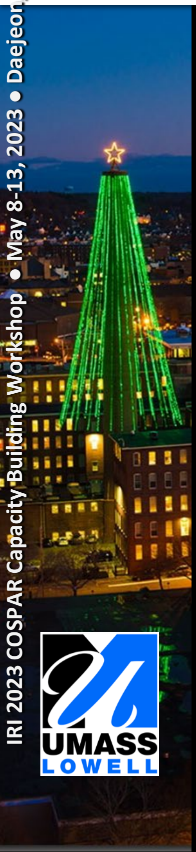
Maximum Usable Frequency

HF communications management

MUF Depression Monitoring

TECHNIQUE	APPLICATION	RATING
1. Local Weather Charts foF2	HF Enthusiasts	Good for NmF2, but only local
2. MUF computation for specific D	HF Enthusiasts	Nice, but only near an ionosonde (local)
3. Negative phase detection from foF2 or VTEC timeline	PECASUS	Good start
4. ΔMUF(3000) from foF2 and hmF2 maps	PECASUS	Good
5. Ray-tracing through CQP ionosphere nowcast	Specific radio link evaluation	Second Best: a few seconds on a GPU
6. Ray-tracing through realistic ionosphere nowcast	Accurate evaluation of specific radio links	Best, but unrealistic for real-time applications

All techniques are based on the real-time weather evaluation by ionosondes



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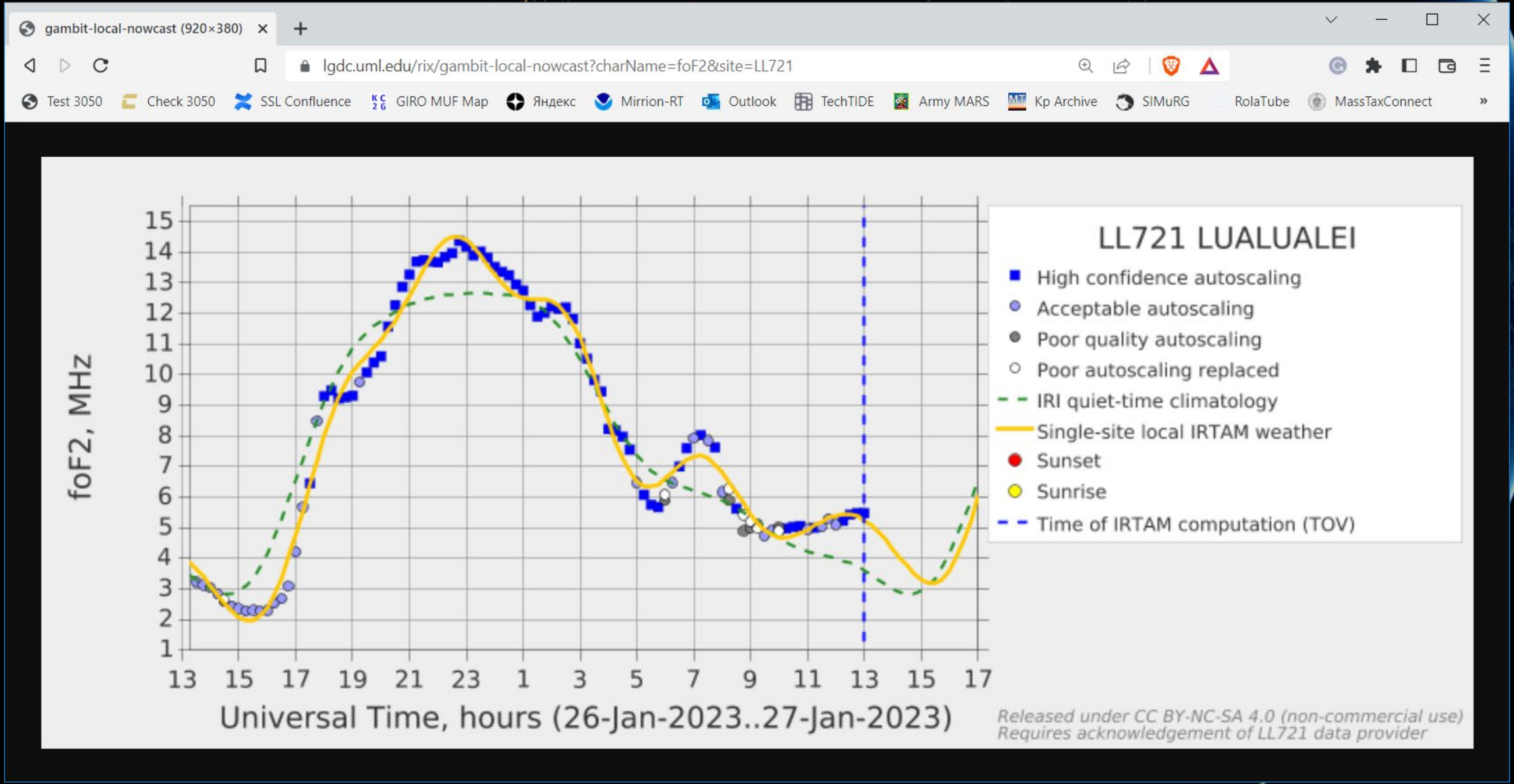
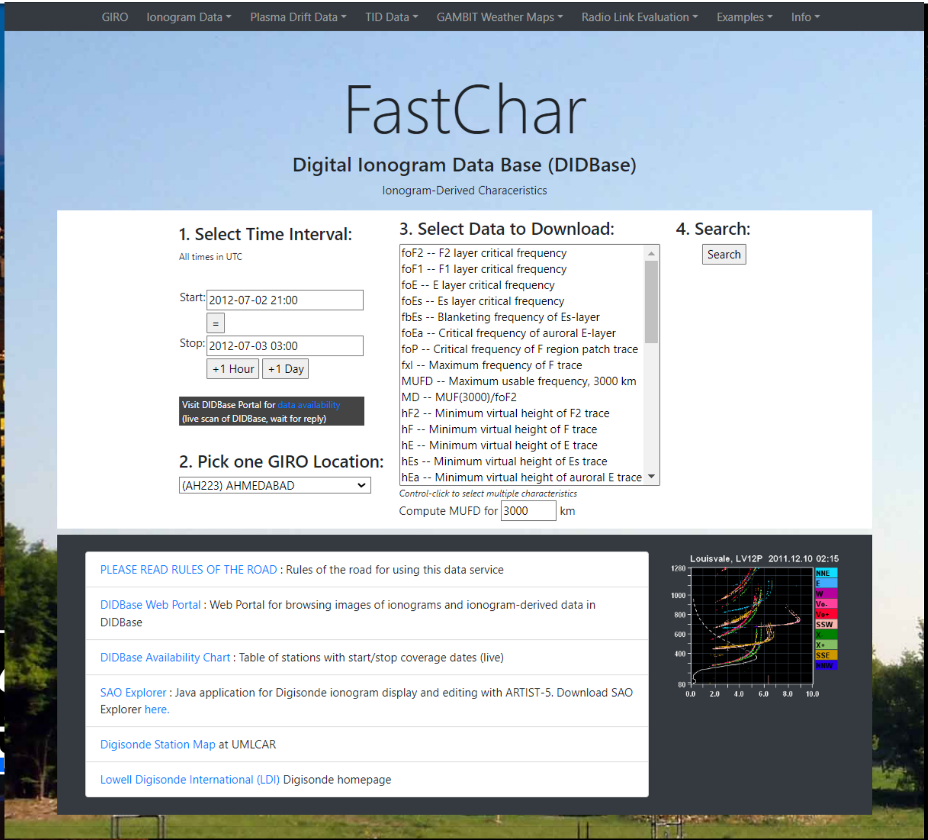
1. Local Weather Charts



2. Fast-Char

fast-access Ionospheric Characteristics

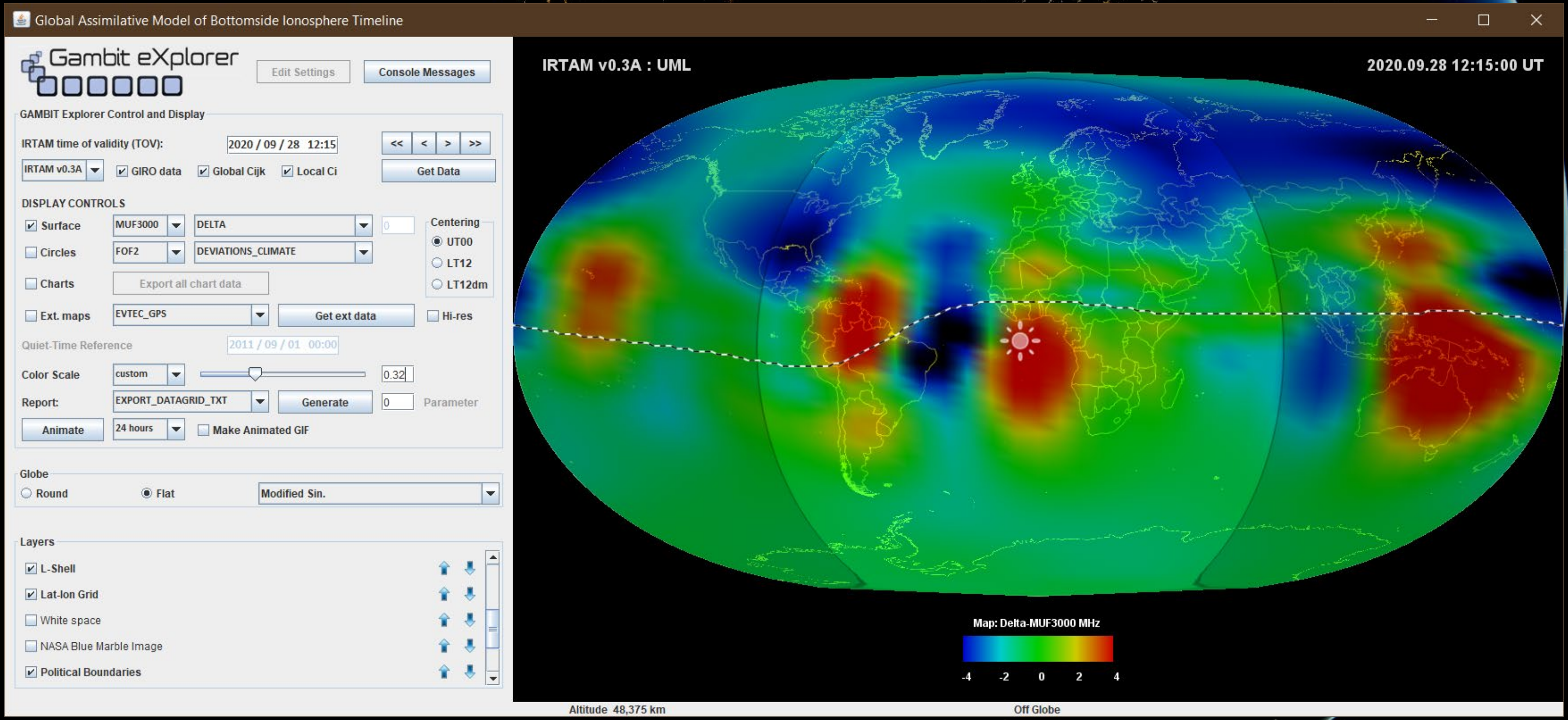


- https://giro.uml.edu/didbase/scaled.php
- Select time, ionosonde, MUF(D), and D

4. Global maps of ΔMUF(3000)

- Use GAMBIT Situation Room

Weather-minus-climate MUF



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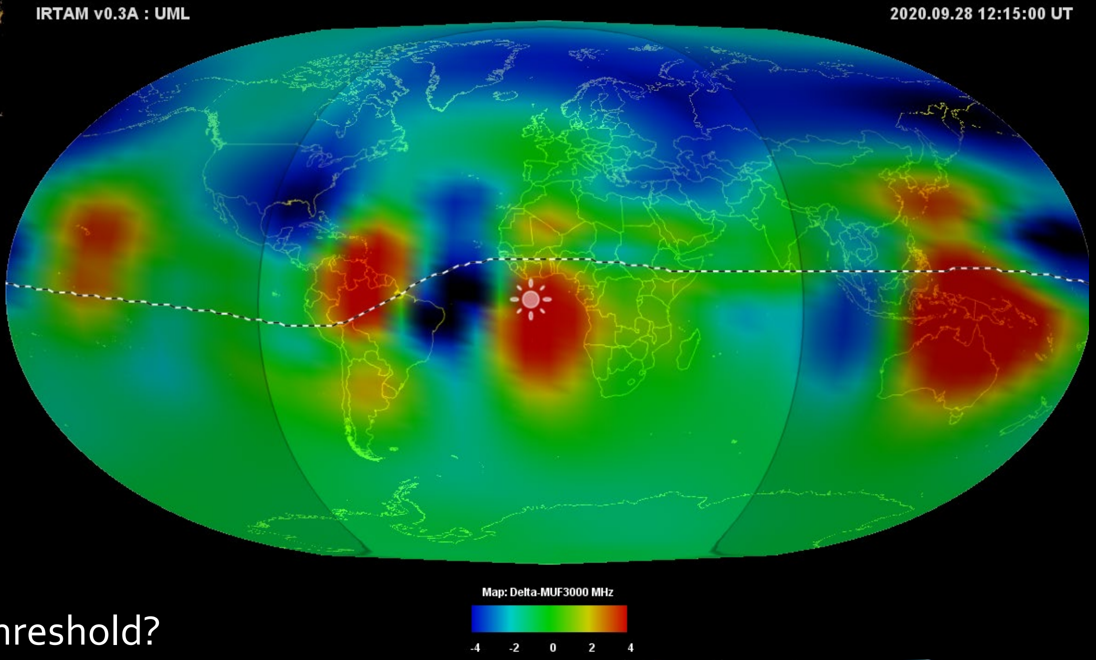
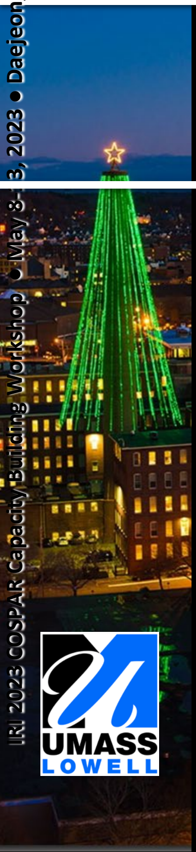
Automatic Depression Detector

Weather-minus-climate
MUF(3000)F2



- Blue blob detection using a threshold?
- Track blue blobs in time and space?
- Significant amount of work done at PECASUS already (Andriy, et al.)

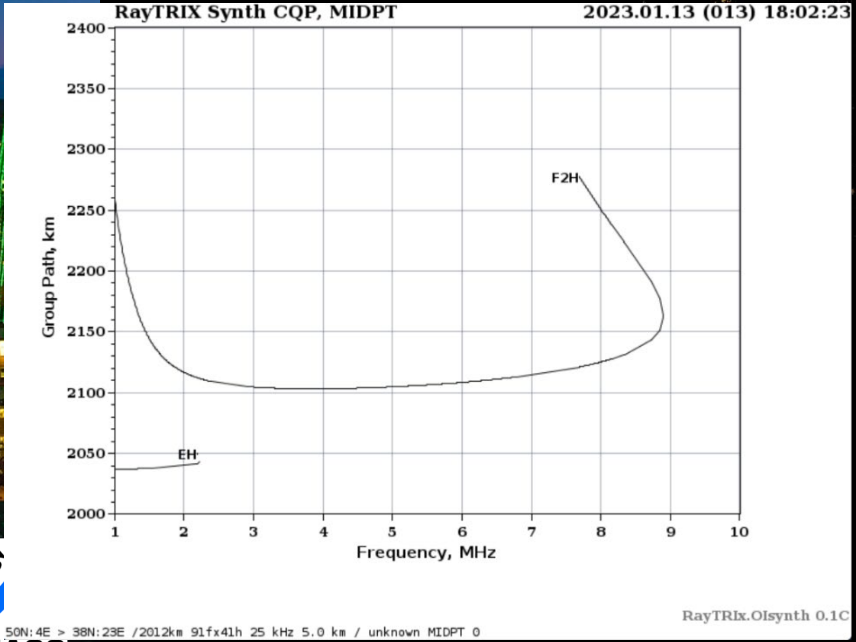


RayTRIX

Ray-Tracing through Realistic Ionosphere eXplorer

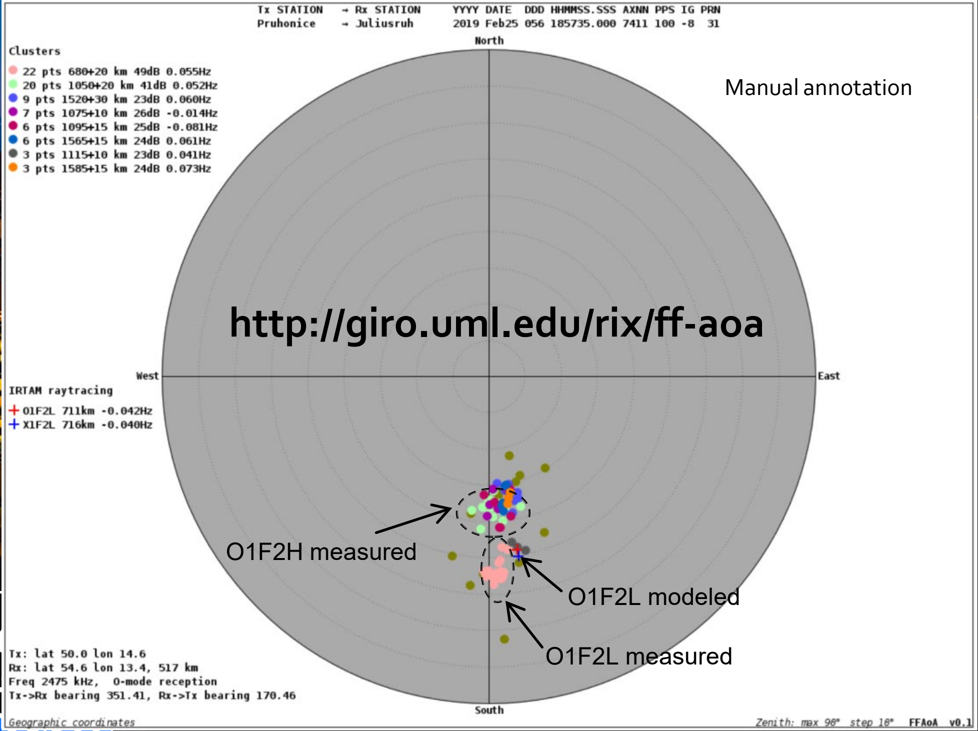
5. RayTRIX with CQP-IRTAM

Dourbes-Athens



- Oblique ionogram synthesis
  - Full range of frequencies
- Based on IRTAM and CQP fit
- MUF(D) for any radio link
  - All three layers, but E and F1 data are not used in the assimilation
- Best frequency range for single-mode communications
- Running time: a few seconds

6. RayTRIX with IRTAM



Pruhonice to Juliusruh D2D data courtesy Dalia Buresova (UFA) and Jens Mielich (IAP)

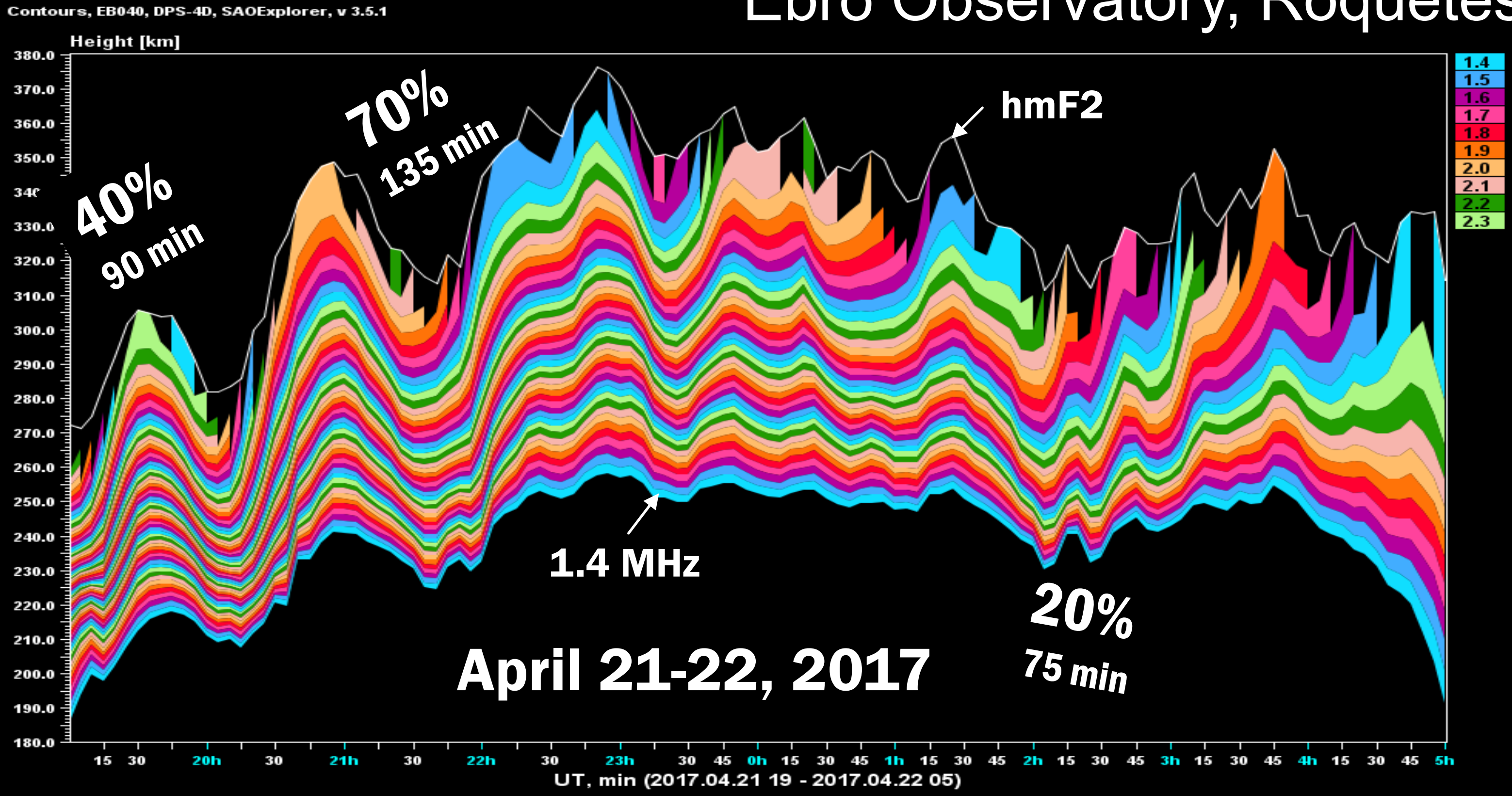
- RayTRIX: Ray-Tracing through Realistic Ionosphere eXplorer portal
- This example is numeric raytracing through IRTAM ionosphere
  - One frequency
  - One propagation mode
  - Two polarizations
- Raytracing is overlaid on D2D skymap measurement from Pruhonice to Juliusruh
  - Raytracing: crosses
  - Measurements: circles
- About 20 second computation time on a regular PC

TID Evaluation and Forecast

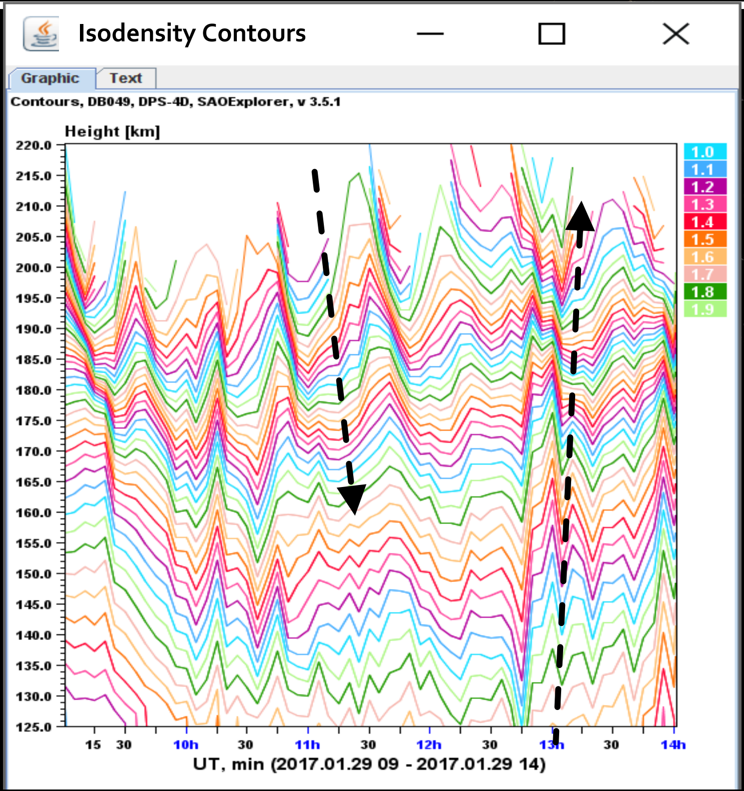
T-FORS PROJECT / HORIZON 2020

TID Detection

Ebro Observatory, Roquetes



HF versus other TID sensors

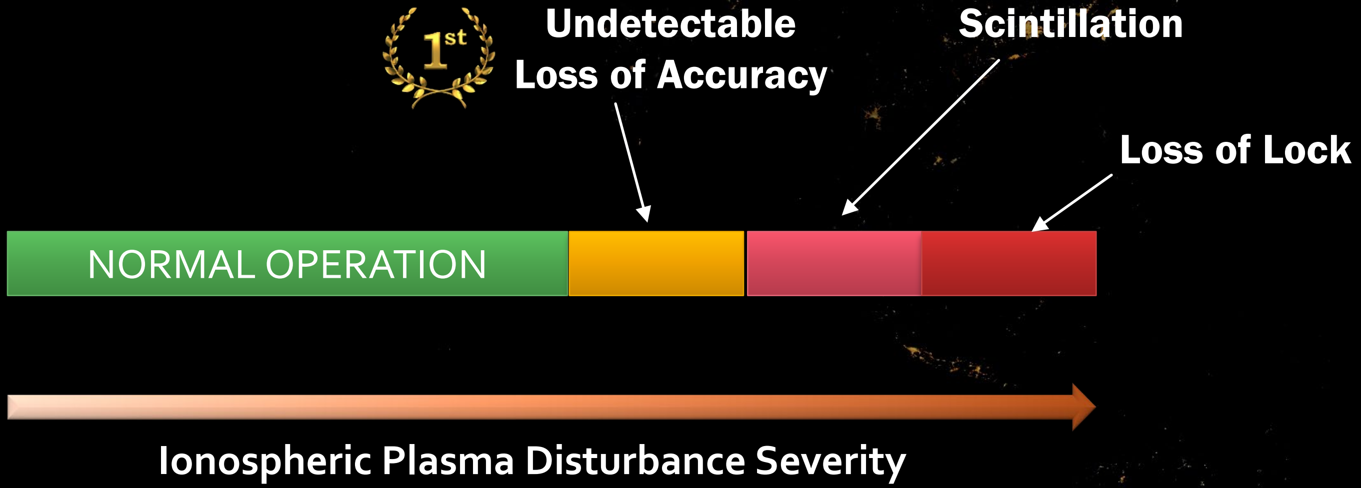


Data courtesy Tobias Verhulst, RMI

- **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**
- **Direct measurement**
  - Static platform (no motion effects)
  - No slant-to-vertical transformation needed
- **24/7 operations with automatic intelligent system analysis**
  - Replicate human intelligence

TID: Silent Accuracy Killer

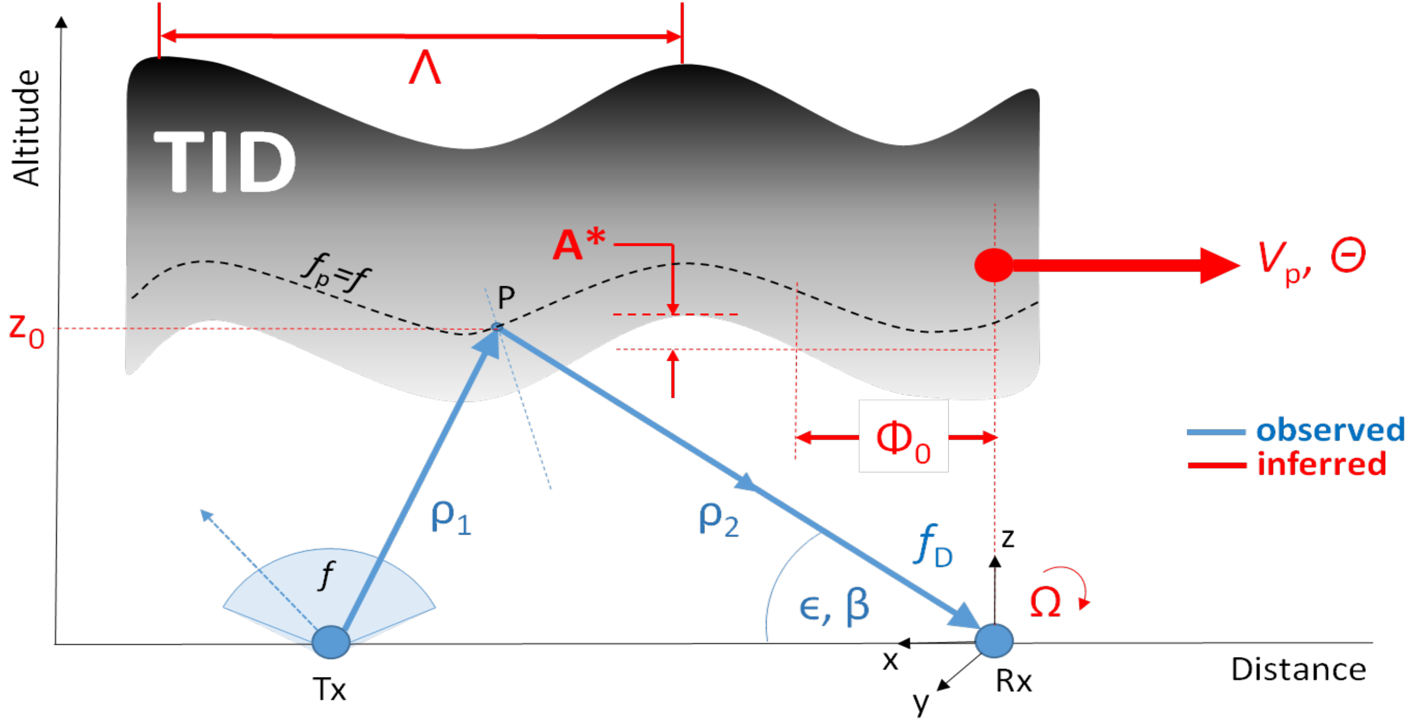
GNSS-DRIVEN NAVIGATION PROBLEMS



TID Evaluation using D2D and FAS

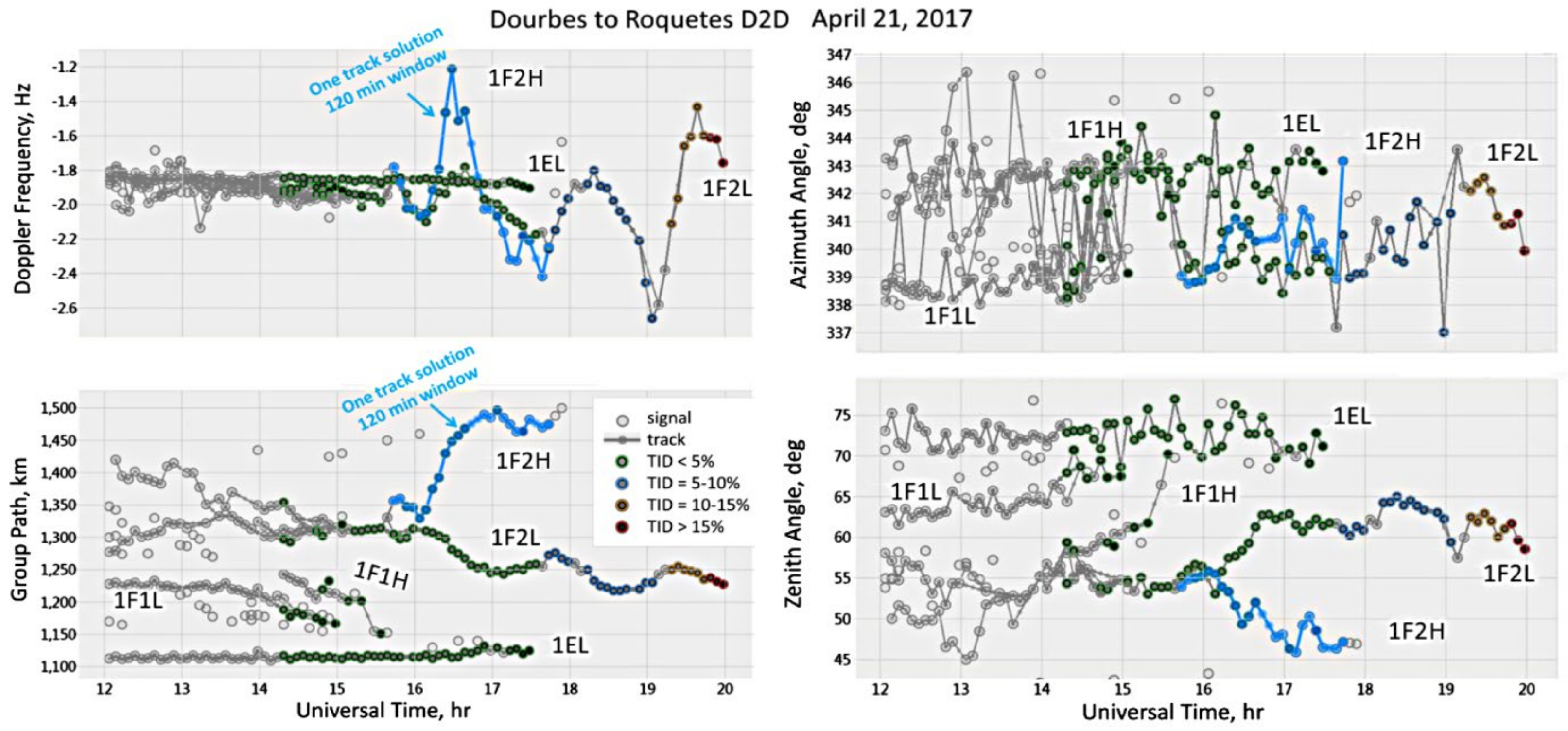
HF Pulsed sounding with multi-path resolution

$$N(z_0, t; x, y) = N_{bg}(z_0, t; x, y)\left[1 + A_N \cos\{\Omega t - K[x\cos\Theta + y\sin\Theta] + \Phi_0\}\right]$$

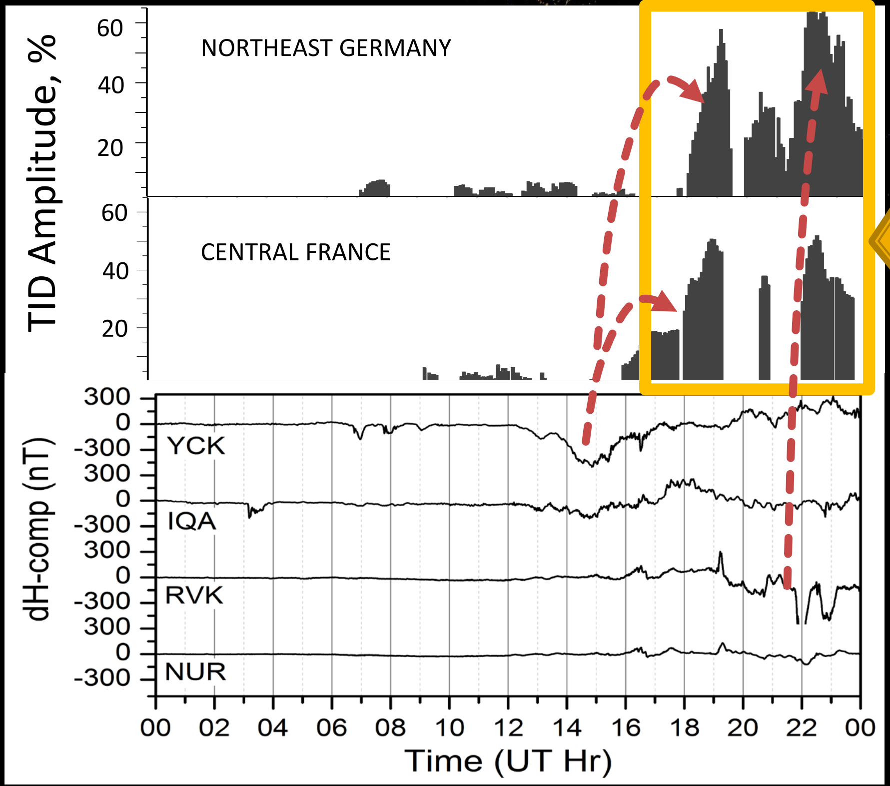


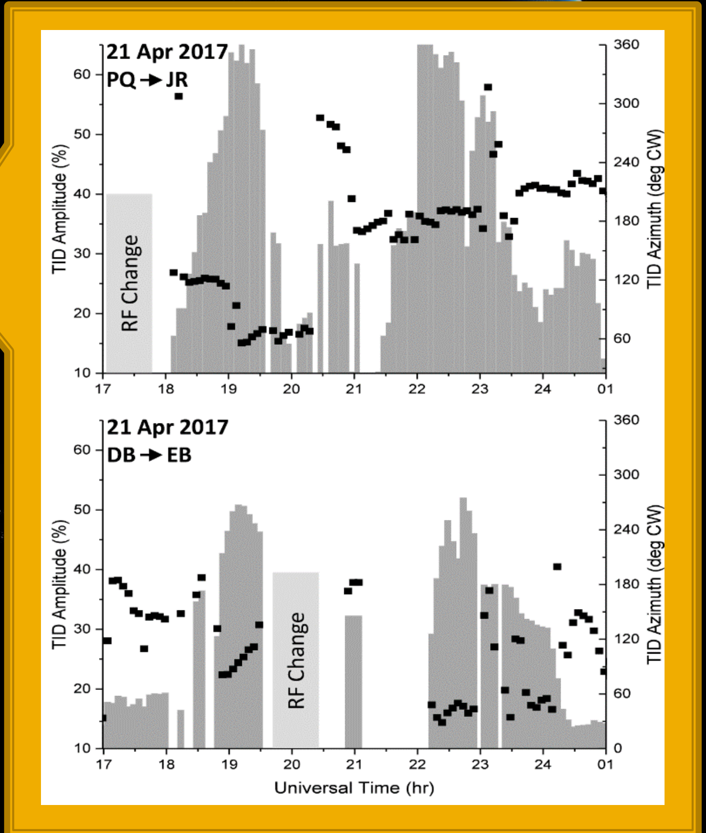
Automatic Signal Tracking

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



The Case of a Traveling Disturbance…

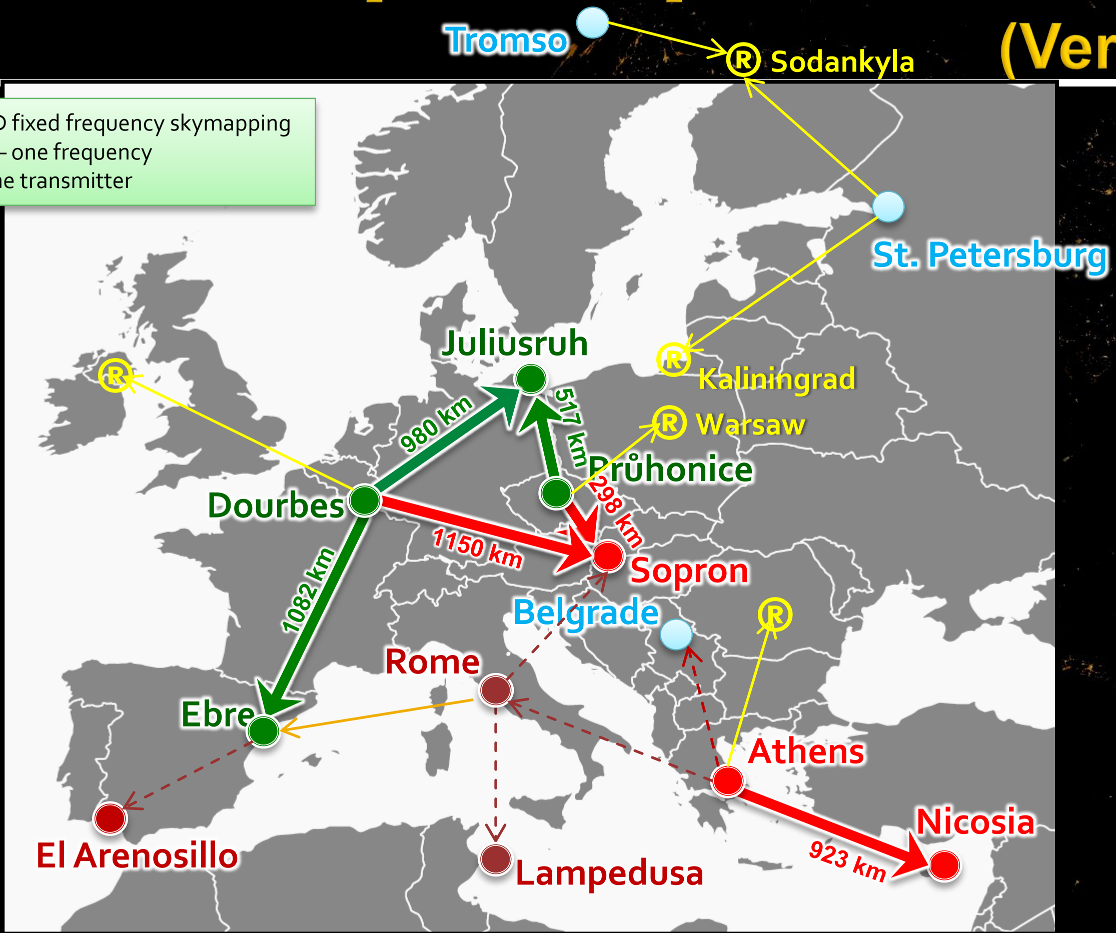




European pilot D2D network

(Verhulst *et al.*, 2017)

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

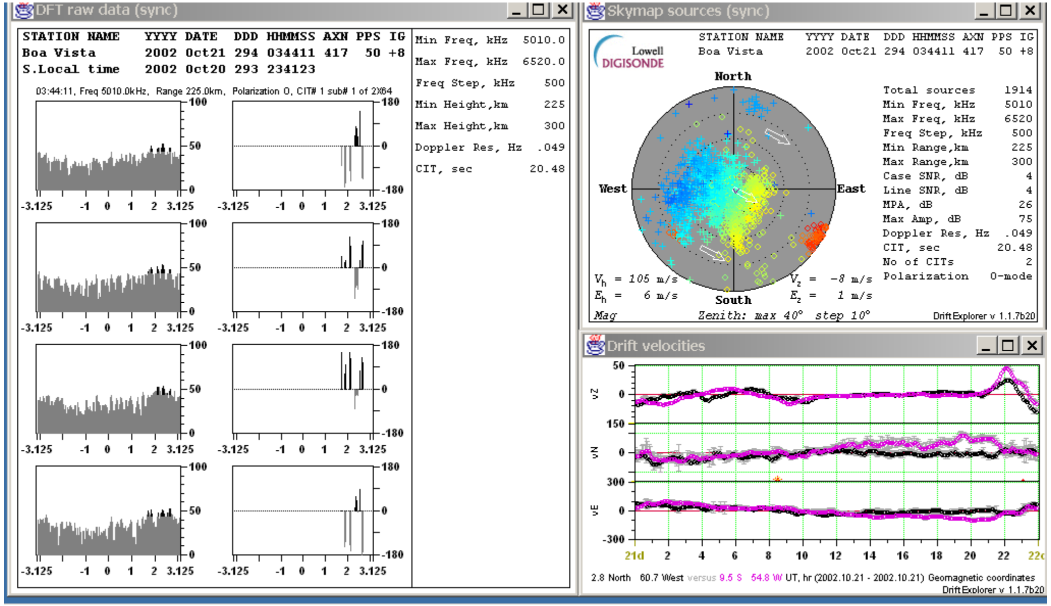


- Phase I links
- Phase II links
- Upcoming DPS4D sites
- Potential DPS4D sites
- Possible DPSR sites

Skymapping the ionosphere

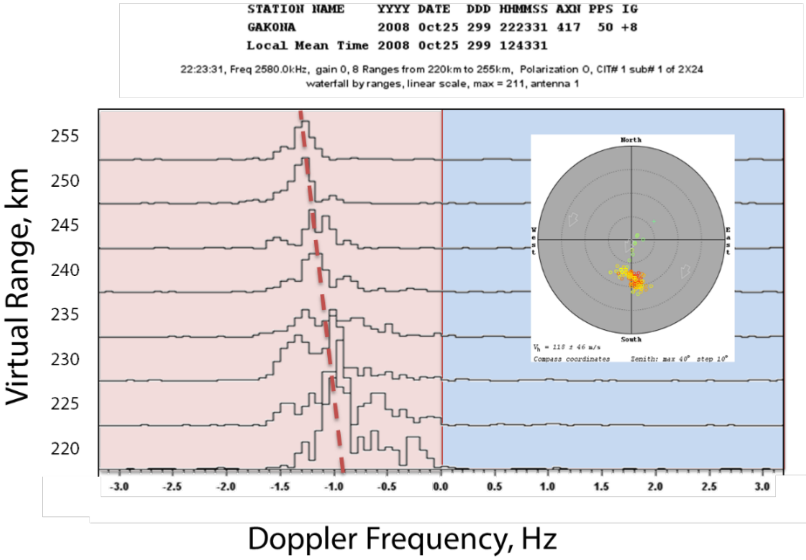
SkyLITE: Skymapping for Local Ionosphere Tilt Evaluation

Plasma Drift and SkyLITE



4-channel data

Skymap & Vector Drift Velocity



HAARP Heating Experiment

AI for IRI

Ionosphere Forecast based on IRI

Outline

- “Triggered” forecast of anomaly
- Alexa, play Storm by Kp=7
- SHAZAM! Associative Memory of drivers
- Dynamic Time Warping (DTW)
- Chat GPT for context evaluation

"Storm" option of NmF2 in IRI

FORECASTING MODEL FOR UP TO 24 HOURS AHEAD

{Ap} ⟶ $\Delta NmF2(lat, lon, t_{fore})$

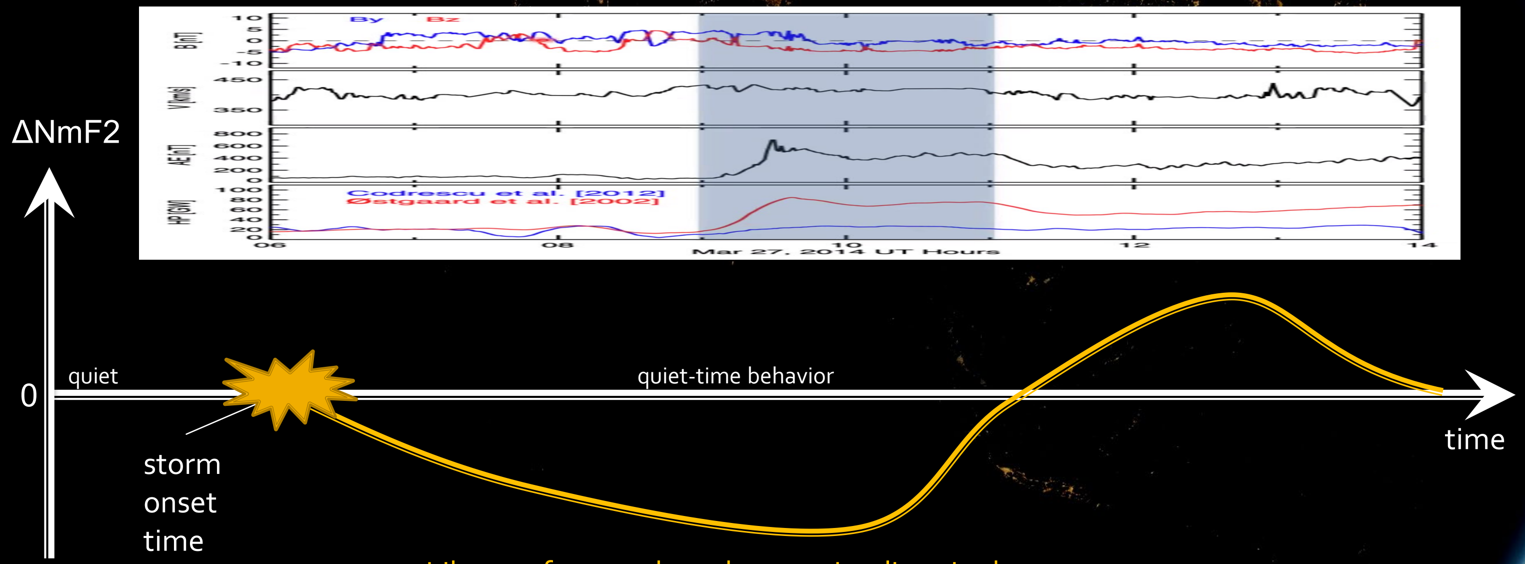
$t_{fore} = (t, t + 24$ hrs

Research funding agencies:
but this is an empirical storm model… oh well

- "Storm" option for NmF2 forecast in IRI, [Fuller-Rawell et al, 1999]
  - Ap is tested for a threshold value to determine if the day is **quiet** or **disturbed**
  - This is an "average" **storm behavior** of ionosphere on disturbed days
  - The storm behavior is stored as ΔNmF2 for any location and forecast time up to 24 hours ahead
- Other "storm" options are pursued based on this principle
  - Blanch and Altadill [2012]

“Remembered Timeline” option

HELIO/GEOSPACE CONTEXT OF THE STORM



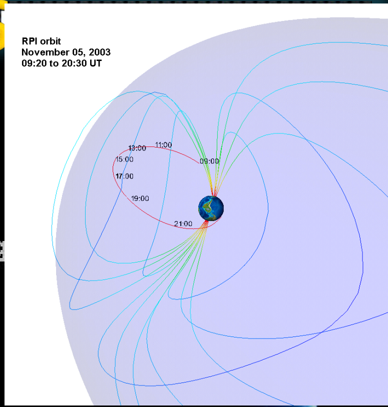
Library of remembered storm timelines in the context

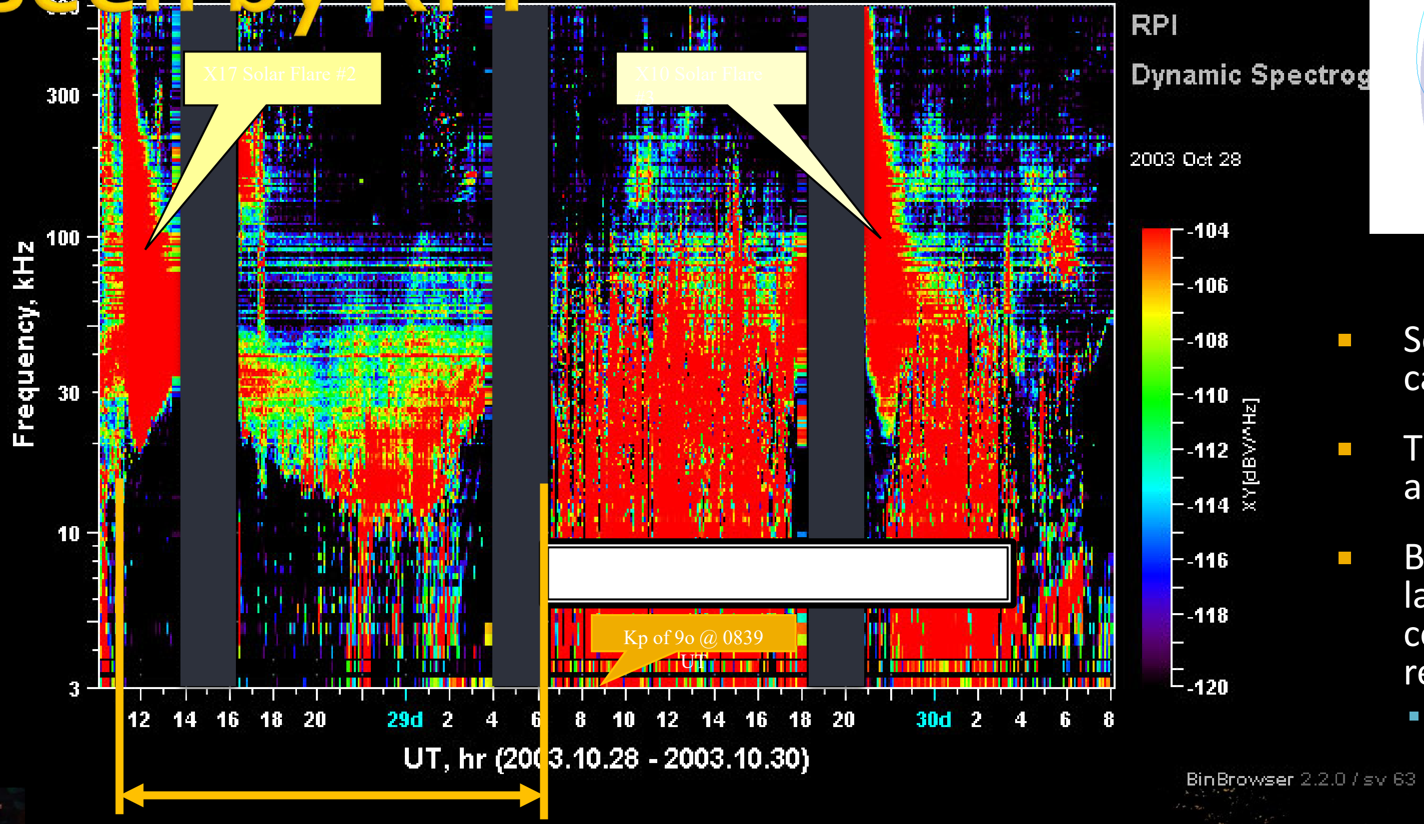
Next step: Library of the storm timelines

instead of the "average storm timeline"

- Instead of an "average" storm, keep a library of previous storm timeline of ΔNmF2
  - To forecast, just find the most relevant storm in the library
- Each timeline must be remembered in the context of the activity in the Sun-Earth environment
  - i.e., not just replay of the storm using one "trigger"
  - Need to build a grand timeline 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*

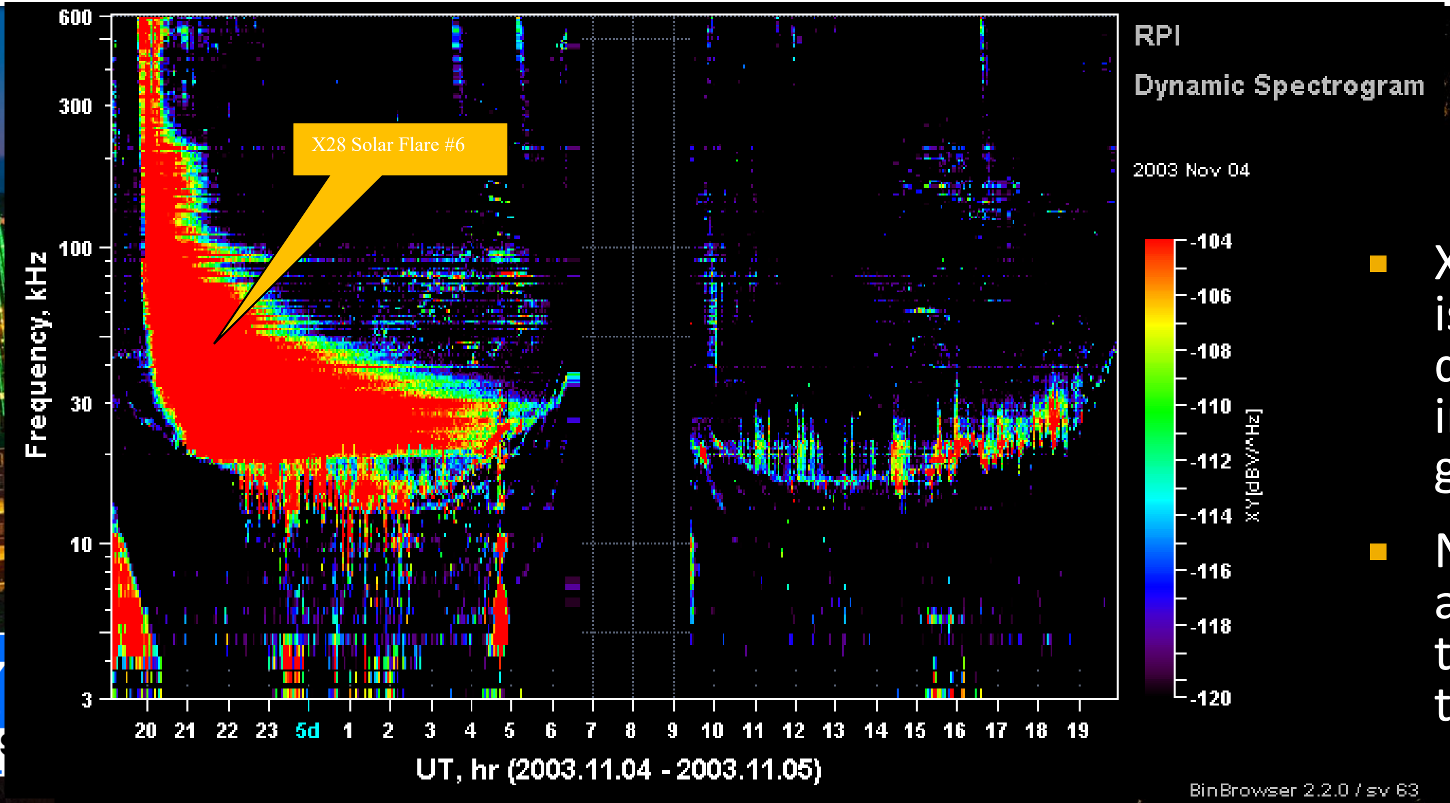
Example: Halloween storm as seen by RPI





- Solar wind velocity can vary
- Timelines will vary as well
- But… natural language AI will come to the rescue!
  - varying speed of words

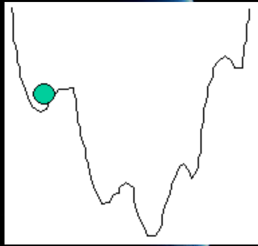
Unrelated example: mega-flare 6 days later

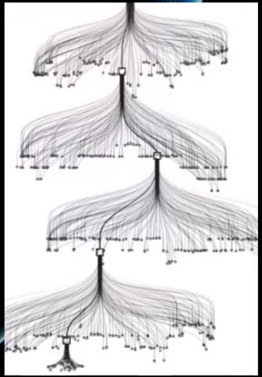


- X28 ranking is questioned: instruments got blinded!!
- Nothing arrived to the Earth, though

Alexa, play Yesterday by The Beatles

- "Yesterday" is interpreted in the context of "play"
  - Not a reference to one day earlier
  - A title to be fetched from the database of song titles
- DEEP LEARNING: multi-layered recurrent (feed-back) network topologies
  - Support interpretation of subelements in the context of other cues
    - Starting position of NN (the green ball) is determined from the context
    - Network evolves into the closest stable condition (remembered state)
    - That state propagates to the next layer of the network
  - Appears 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 the interplay of helio- and geo-activity markers



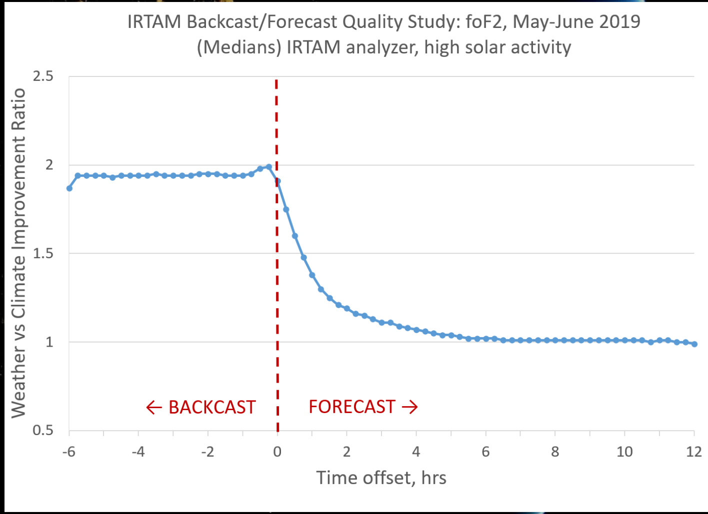


Natural Language AI for space weather?

- Detect “Alexa!”
  - Recognition of the storm onset
    - Solar flare?.. signature of CME?.. Solar wind pressure?.. lots of ideas!
    - Maybe all of the markers must be used to determine reference time
- Then, somehow, interpret the available “Play Yesterday by The Beatles”
  - Extract **context cues** to retrieve the best-matching storyline in the Storm Library
  - Context of the sentence == Context of the relevant system driver storylines
- Retrieve and *process* the closest storm storyline from the library
  - Process? Encoding is needed to avoid varying timing of the processes
    - [to support varying speed of word pronunciation]
- Apply the processed storyline to forecast the upcoming departure of the stormy weather from the quiet-time model
- REPEAT

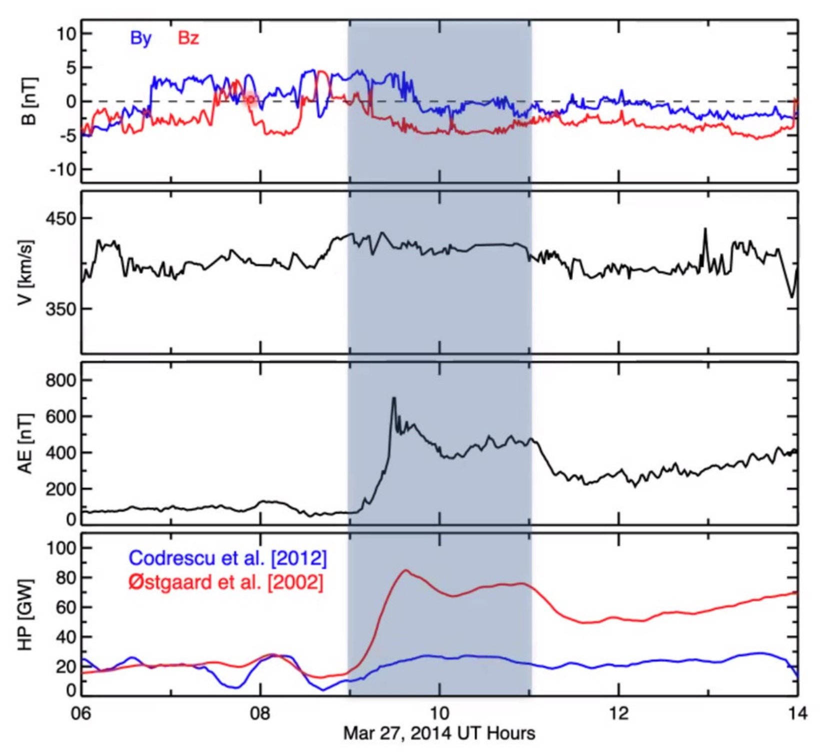
Capturing Context of Ionospheric Dynamics

- Ionosphere: immediate response to external forcing
  - Thus its current conditions do not inform future states
- Need to use storylines of all external drivers as context
  - Cannot be just one instant “triggering” driver (e.g., Kp=6)
  - Driver dynamics is matched (paired) to the ionospheric storm dynamics
    - Across the complete forecast storyline from onset to end
  - Important: which driver is relevant out of the set? (Deep Learning helps; *inductive bias*)

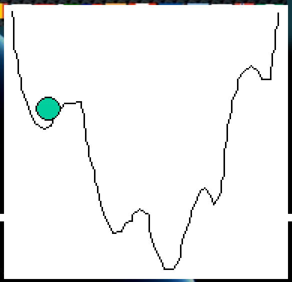


Why "REPEAT" step is needed?

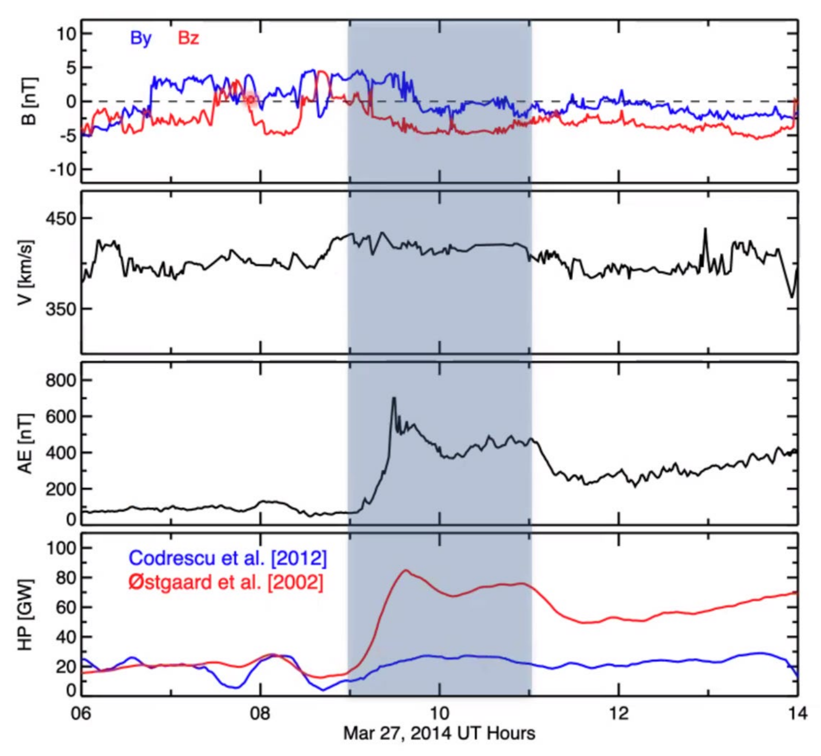
- Ionospheric response to the storm-time impacts is not just a "triggered option for a disturbed plasma day"
  - Context of the disturbed ionosphere dynamics is a continuous function of *t*
    - Driver storylines need to be complete to retrieve the best matching storm in the library
    - But in the forecast scenario, only an initial fragment of the storylines may be available
- Forecast shall be repeated as time progresses and larger fragments of the storylines become available



How to get storyline from a fragment



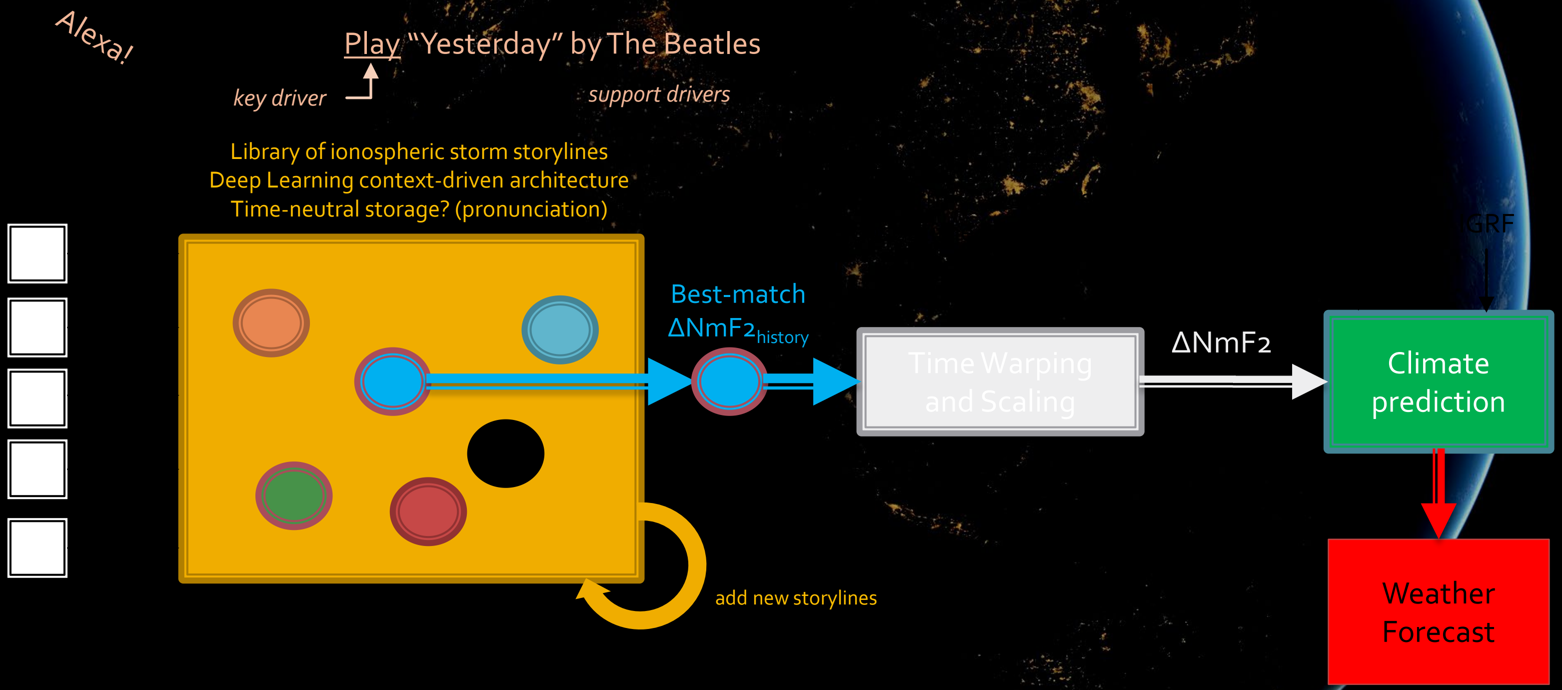
- Note: not the storyline of the storm, but of the storm *drivers*
  - Simpler task… *divide and conquer*
  - It is the interplay of drivers that matters
- Associative Memory is one possibility
  - Used in recognition of handwriting
  - Also for recalling stored data from their noisy and incomplete realizations
- Recursive, feed-back NN architecture
  - Hopfield networks
  - No input layer, no output layer
  - Neurons are clipped to available data and evolve into the nearest local minimum of E



PITHIA-NRF and T-FORS: European SWx

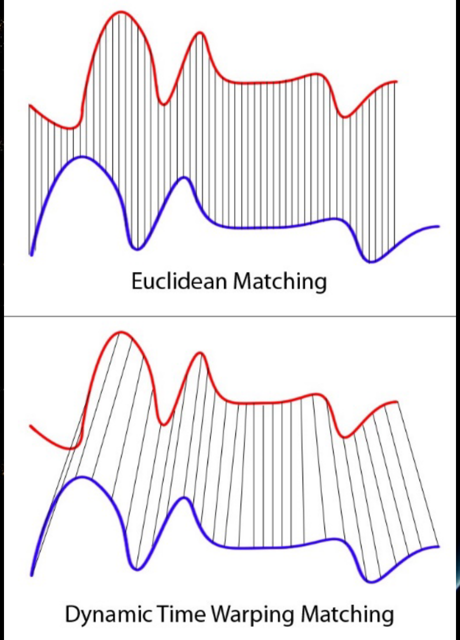
- Real-time data for forecasting by historic analogy are not easy to come about
  - Need a consortium of real-time data providers
- PITHIA-NRF is an emerging space physics data infrastructure in Europe
  - Look it up! www.pithia-nrf.eu
  - HORIZON 2020 project
  - Based on EGI Foundation mega-facility of computing resources
    - Public funding = better prospects of longevity
  - And a Network of Research Facilities (BRF)
    - some facilities have decades of uninterrupted operation
  - T-FORS is the pilot project to leverage PITHIA-NRF collections
    - TID Forecasting System
    - HORIZON 2020 project
    - Listen to Elvira Astafyeva talk later this morning (TID)

Forecast Architecture

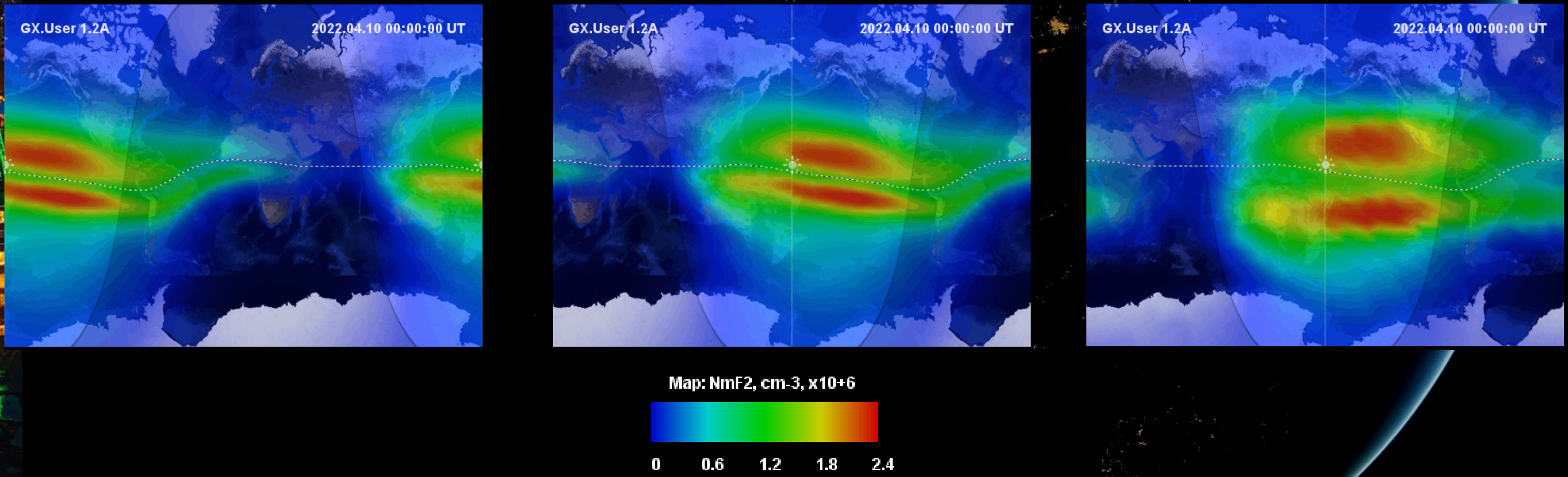


Dynamic Time Warping (DTW)

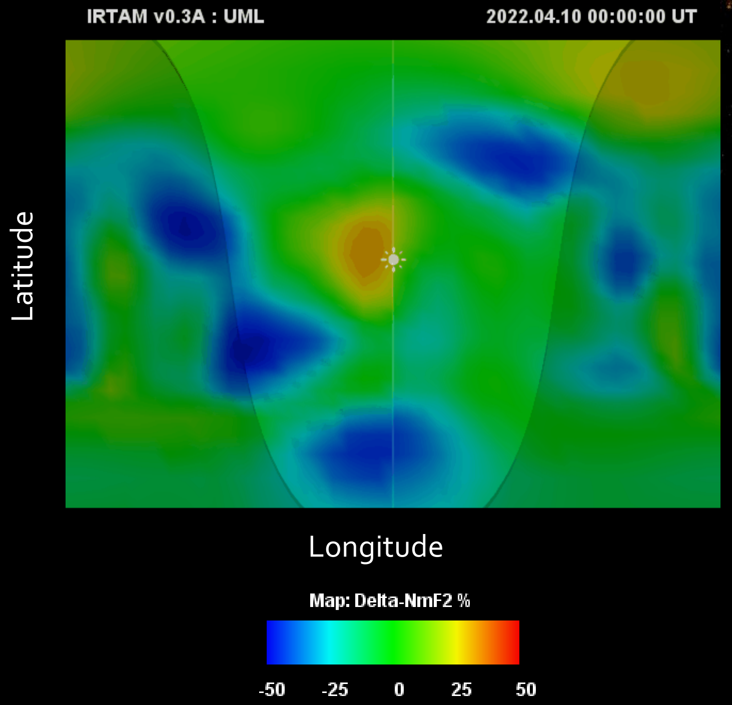
- Warp library-provided storm storyline
  - DTW finds similarity between 2 storylines
  - Driver storylines may be indicative of *how different* the actual storm timing is from the Library copy
  - Corresponding time warping shall be applied to the correction ΔNmF2



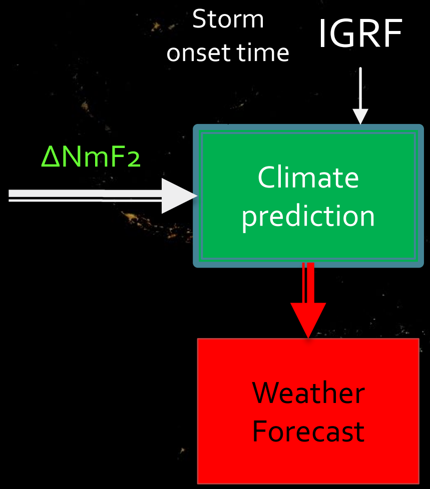
Library of storms in a longitude-neutral form



Encoding library storylines of ΔNmF2



- Total 1024 coefficients to store 24 hour global animated 2D maps ΔNmF2
- Can be expanded to 2048 coefficients to store 2-day storyline



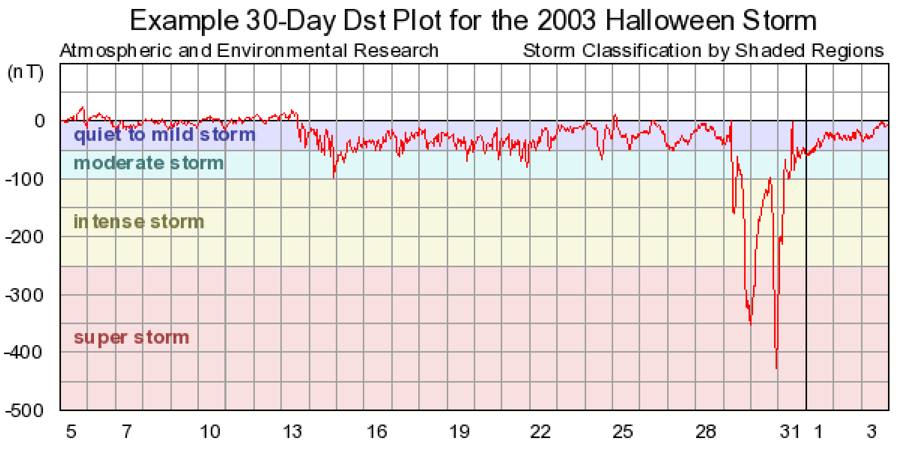
The IGRF model of the Earth magnetic field is needed to re-magnetize the retrieved library

Forecasting by context-driven memory

- 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*
  - Associate the timeline of ionospheric dynamics with timelines of ionospheric state drivers
    - Deep Learning: placing the storm vocabulary into the context of a "sentence" of ongoing geospace activity
    - Rely on NN superior inductive bias to build the context
    - Plus other tricks:
      - Dynamic Time Warping (DTW)
      - Associative memory (AM)
        - Restore a driver's full storm timeline from its initial observed fragment
      - Chat GPS ability to glean context and build output

Natural Language Processing as DTW example

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



Summary

- Deep Learning “Ice-Break” is ongoing in NN-based forecasting
  - DL learns the system from its previous behavior
- A concept study of DL-based forecast of the ionospheric storm storylines:
  - Forecast deviation timeline of the disturbed ionosphere
    - Deviation from the quiet-time LT-centered/demagnetized ionosphere
  - Sync the deviation timeline to the actual/definitive storm onset time (Alexa!)
  - Use Dynamic Time Warping to maintain a smaller vocabulary of the storm behavior
  - Deep Learning to describe ionosphere timeline in the context of key storm driver timelines
  - For each activity driver, use associative memories to retrieve a full-length storyline from the initially observed fragment
- Procedure:
  - Detect storm onset, obtain full-length driver storylines
  - Take 30-day median current ionosphere, LT-center, de-magnetize,
  - Retrieve deviation storyline from the storm library, time-warp to current activity
  - Apply deviation to the median, position at reference LT, re-magnetize.

LGDC: ~ 600 Mil records

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