Ionospheric Data Assimilation Models

Real-Time IRI Task Force Activity

Ivan Galkin[1,2] and IRTAM Science Team

(1) Borealis Global Designs, Varna, Bulgaria

(2) Space Science Laboratory, UMass Lowell, USA

2nd PITHIA-NRF Training School
with T-FORS support

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    - Metadata Definition Group

GAMBIT SITUATION ROOM

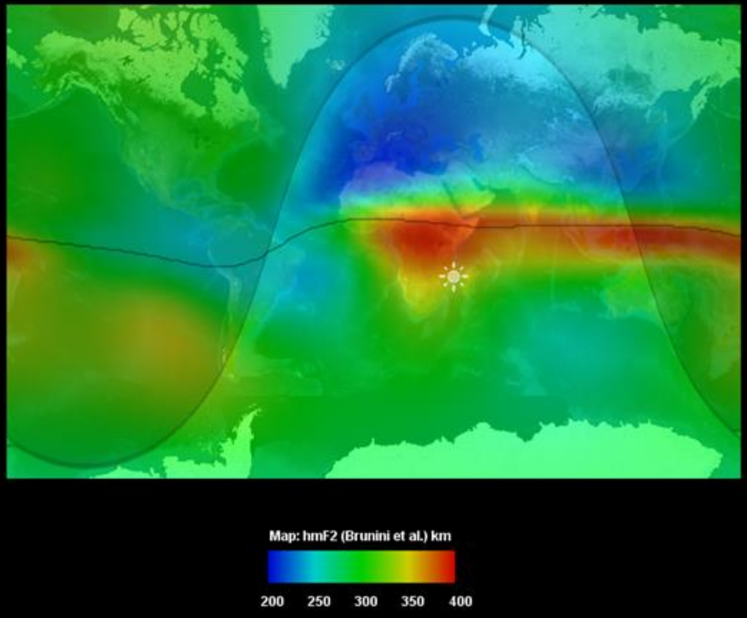
BOREALIS GLOBAL Designs

Outline

- Background:
  - Assimilation concept
  - NECTAR technique for Real-Time IRI
    - Driving data-driven model with data
  - IRTAM and GAMBIT
- Higher data products from GAMBIT system
  - Data fusion of near-real-time IGS and GIRO maps
  - Computation of MUF(3000) weather maps
  - Study of attenuation trajectories for NECTAR spatial prediction
- Open problems

Assimilation Concept: 2D map example

Global background model of hmF2 + **Ionosonde Network Real-Time hmF2** = **Global hmF2 Weather Model**



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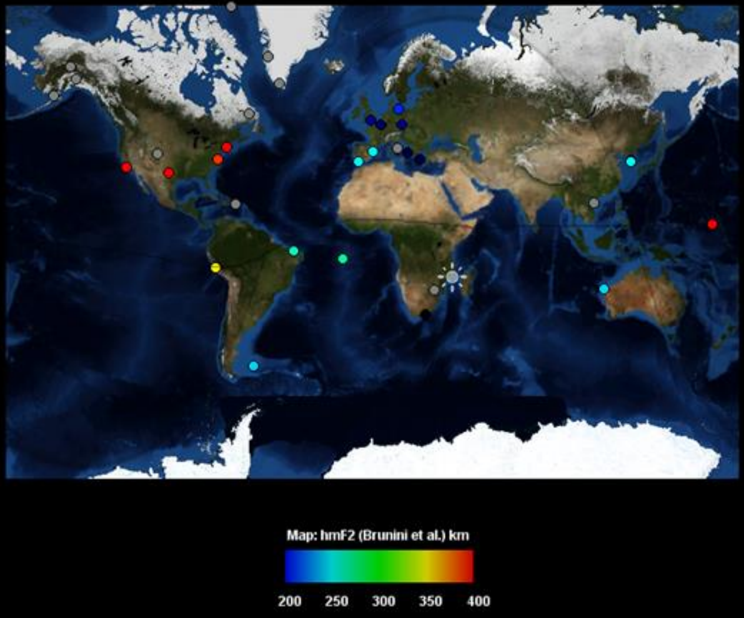

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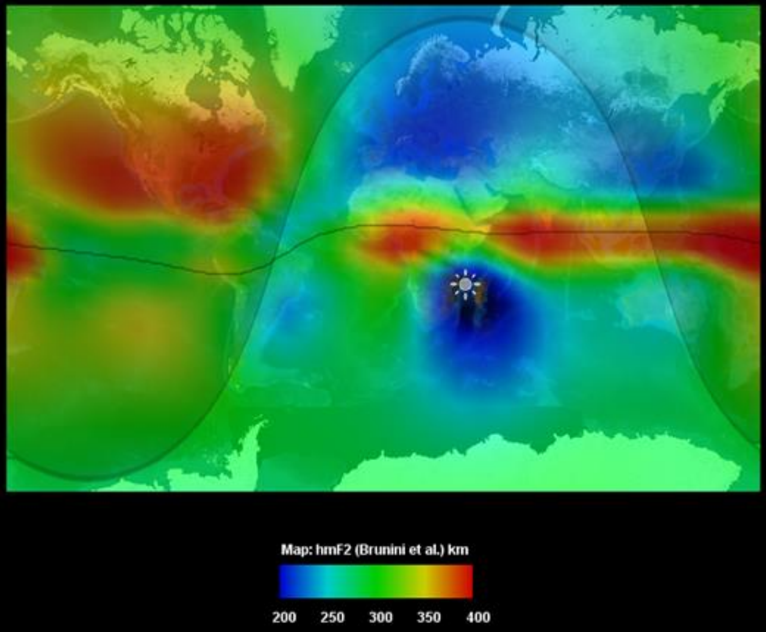
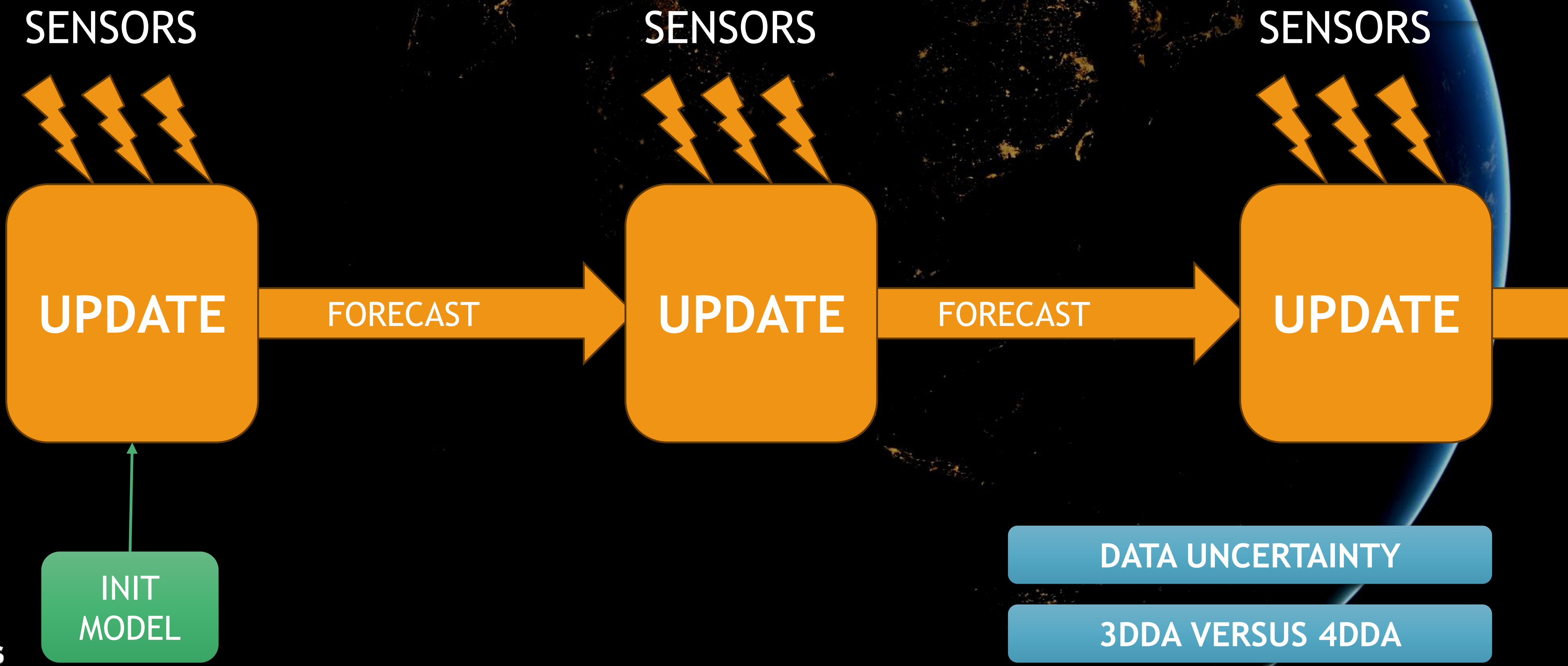


AND NOW THINK 3D

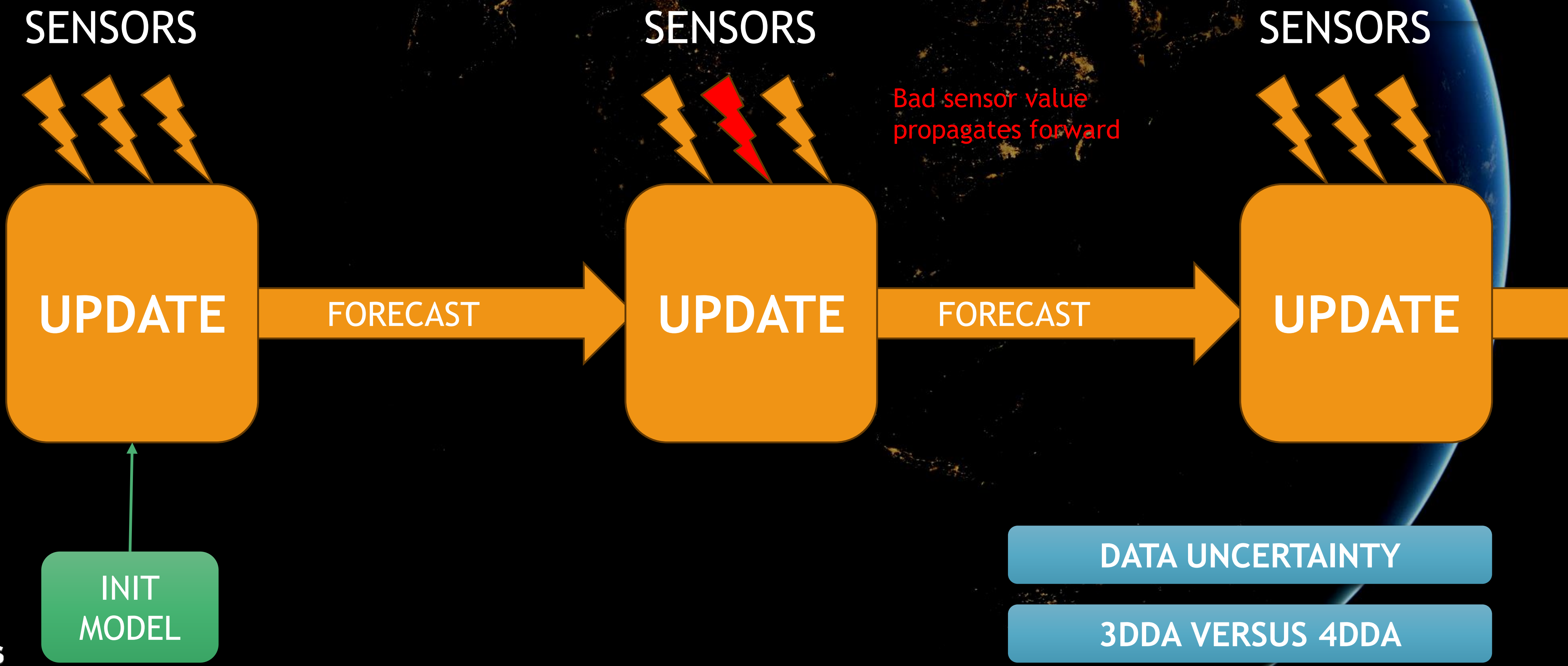
Kalman Filter approach



DATA UNCERTAINTY

3DDA VERSUS 4DDA

Kalman Filter approach

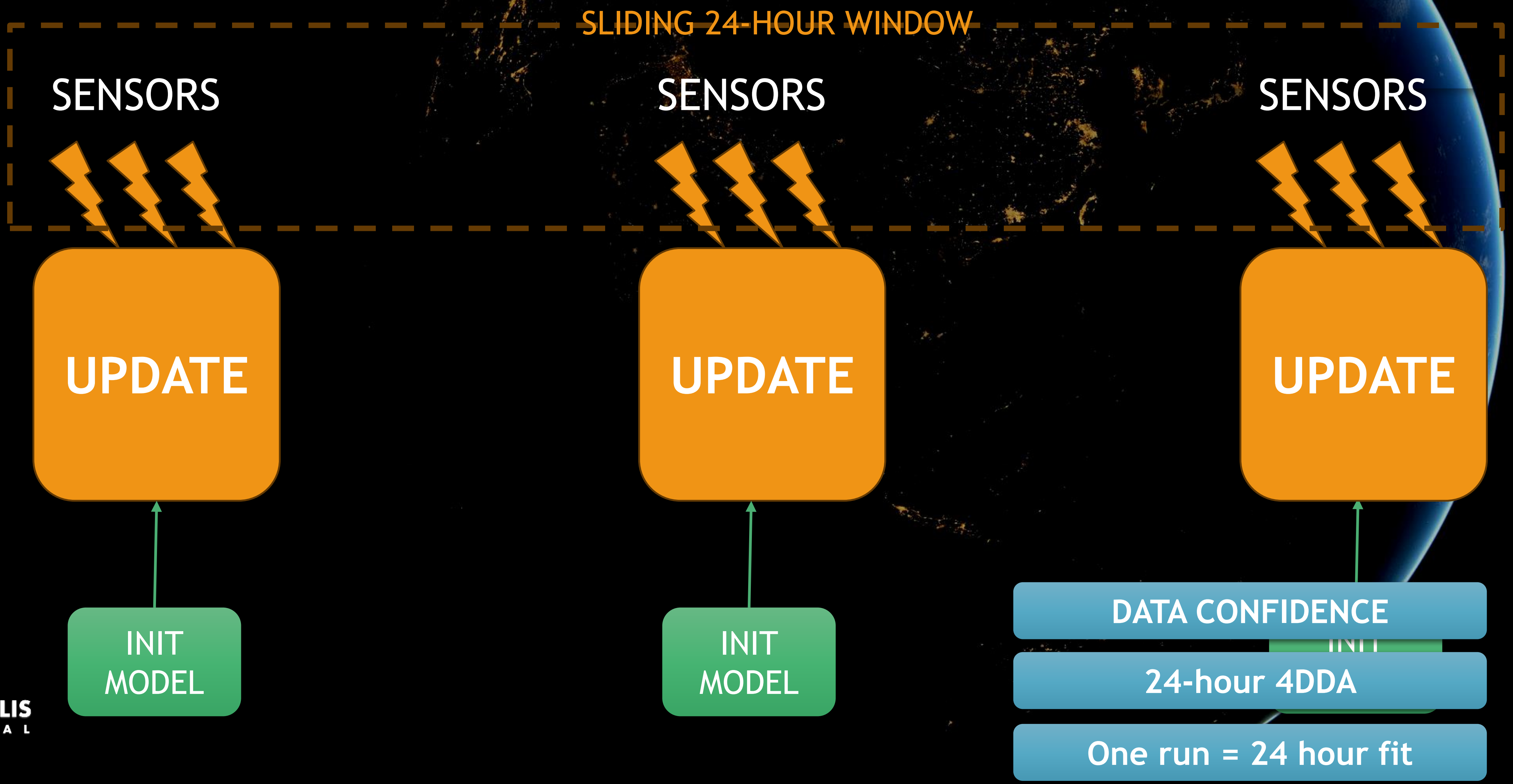


DATA UNCERTAINTY

3DDA VERSUS 4DDA

NECTAR approach

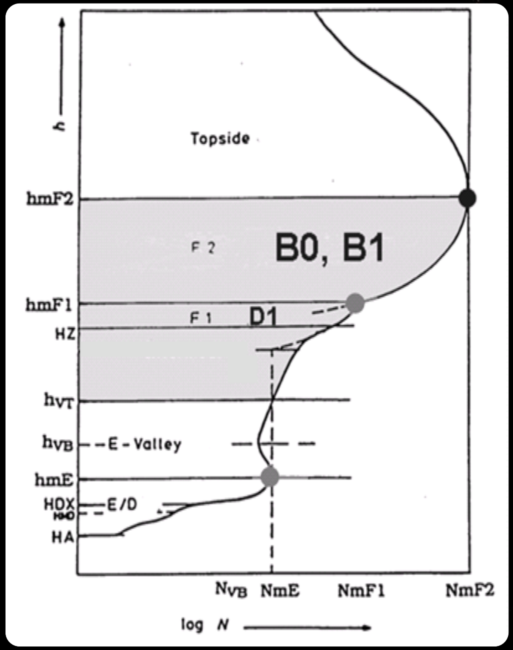
NECTAR



IRTAM = IRI-based Real-Time Assimilative Model

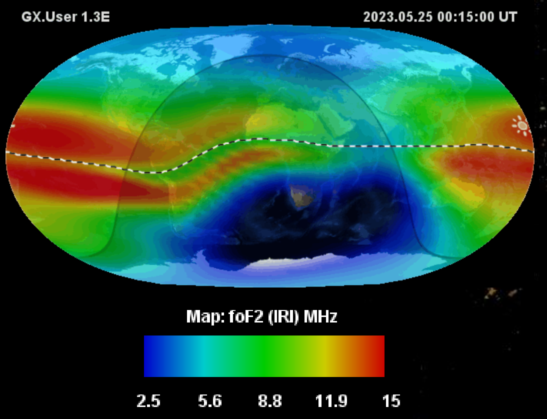
BASED ON NECTAR ASSIMILATION ALGORITHM

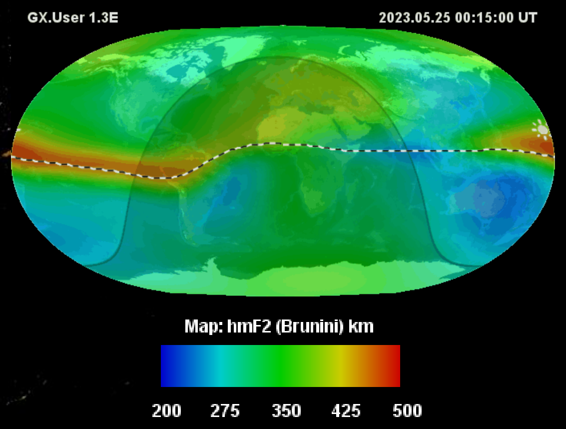
NECTAR



The vertical profile of plasma density:

16 “anchor” parameters





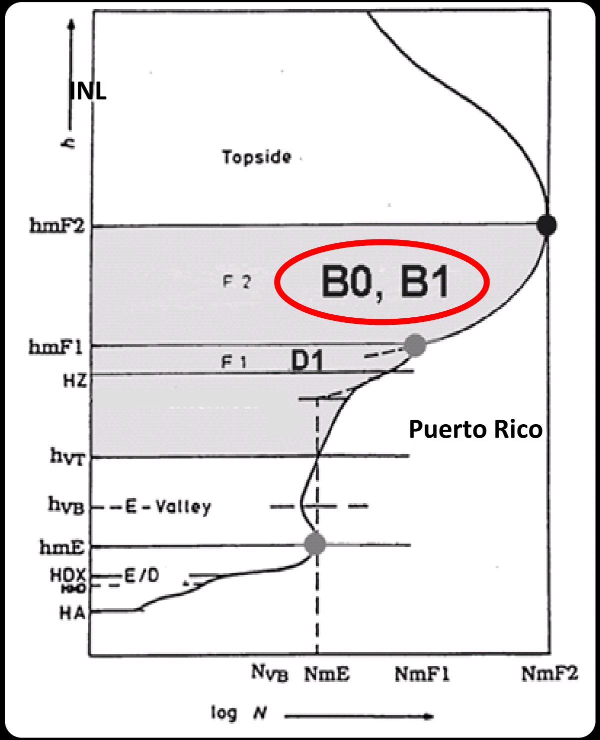
N_mF2 h_mF2

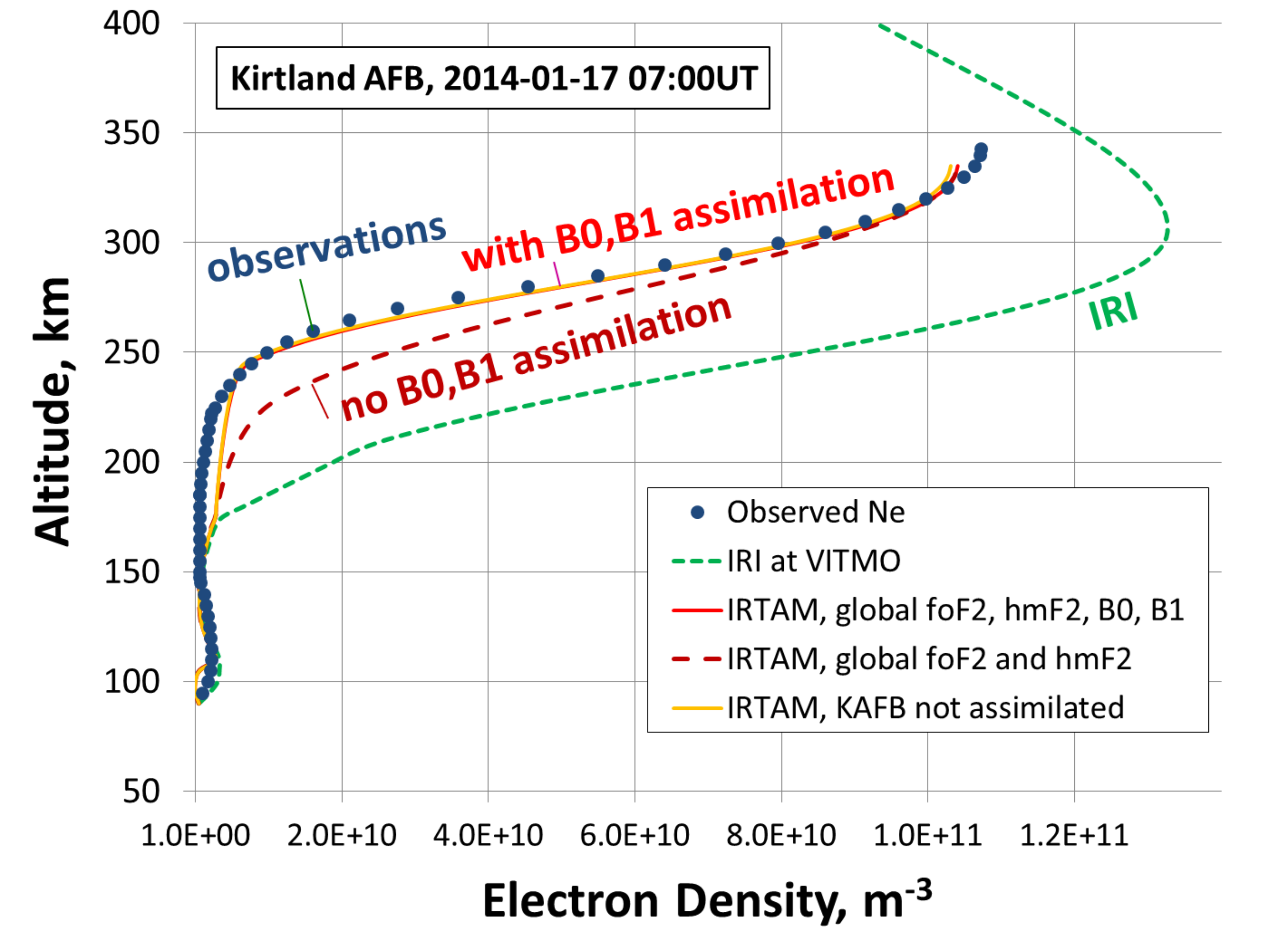
One day in the Ionosphere Life

1-DITIL

BOREALIS GLOBAL Designs

Profile shape is important! assimilate B0 and B1

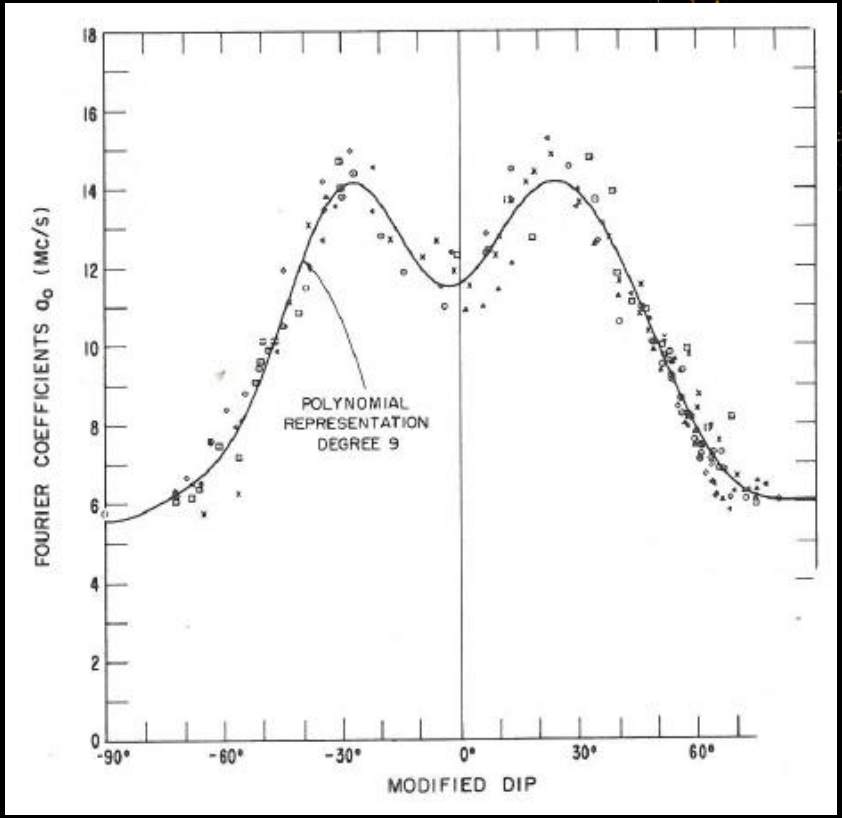




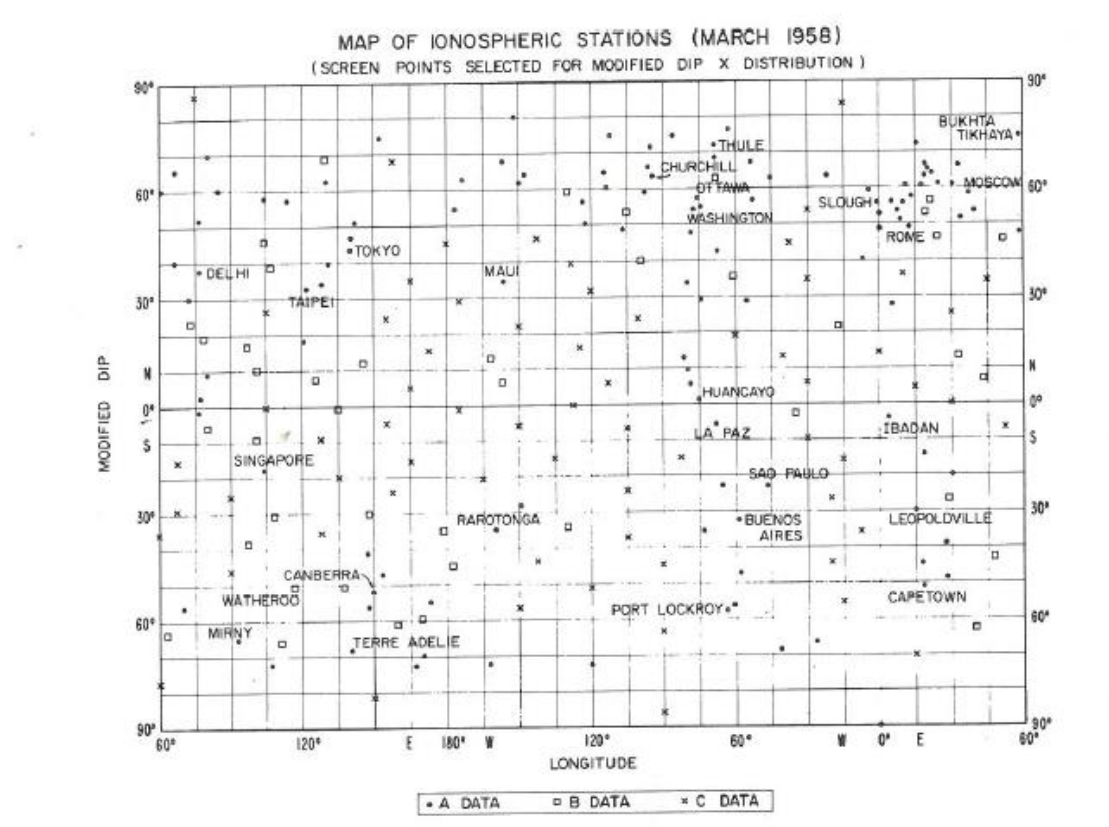
Modeling geosystems using data fragments

A quick demonstration

Gray-box model: “Screen” points

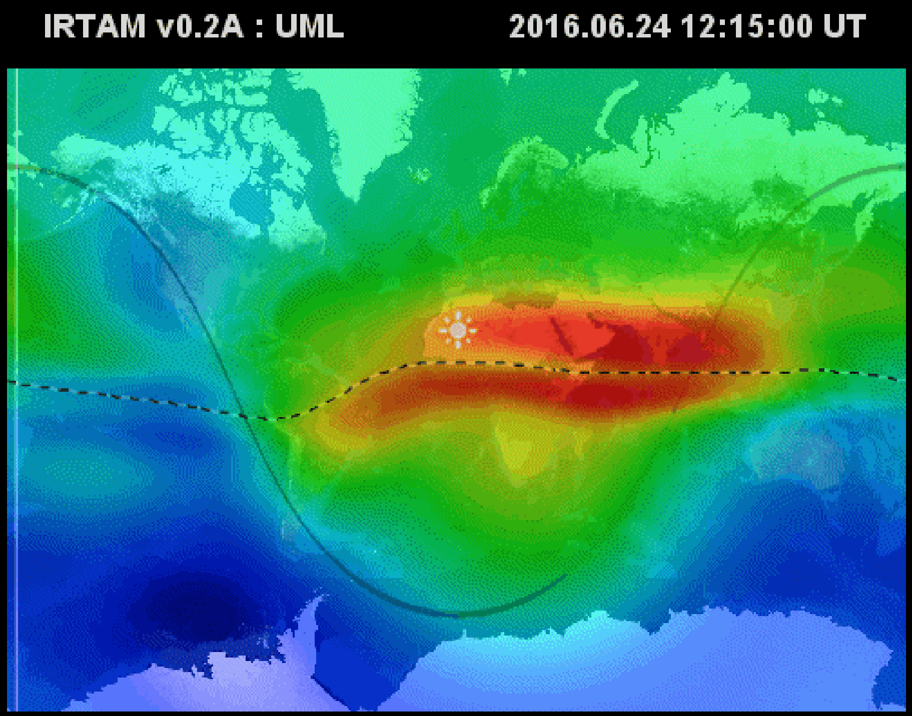


96 ionosondes averaged to represent typical latitudinal variation

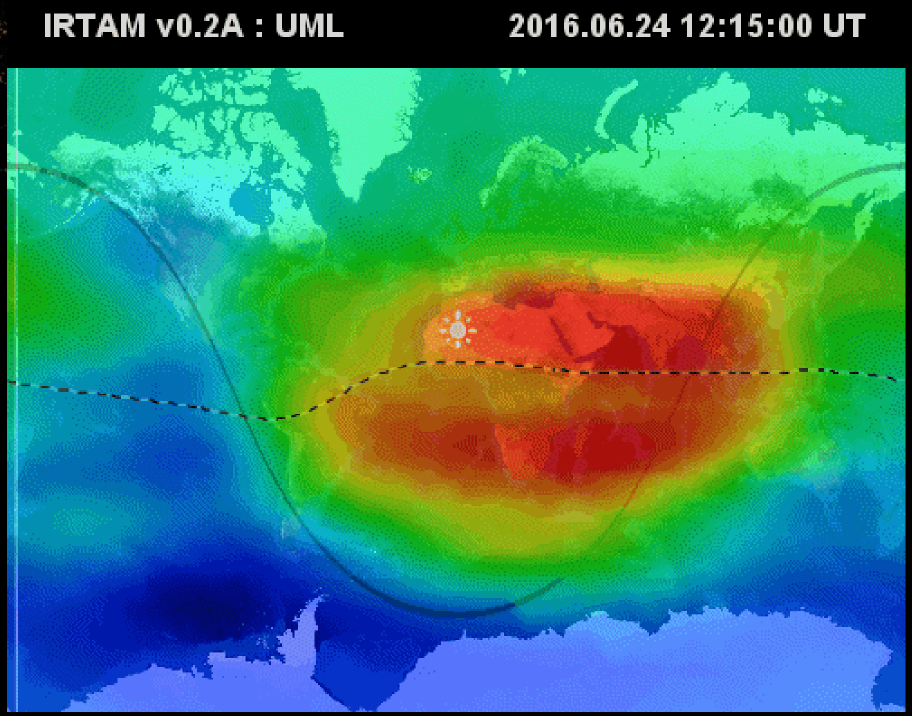


Screen points added with “anticipated” ionosphere

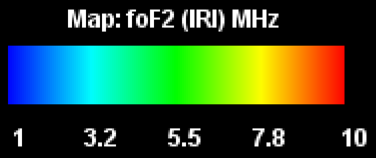
Demagnetize ionosphere before training



Aligned to 12 LT



Aligned to 12 LT
Magnetic field removed



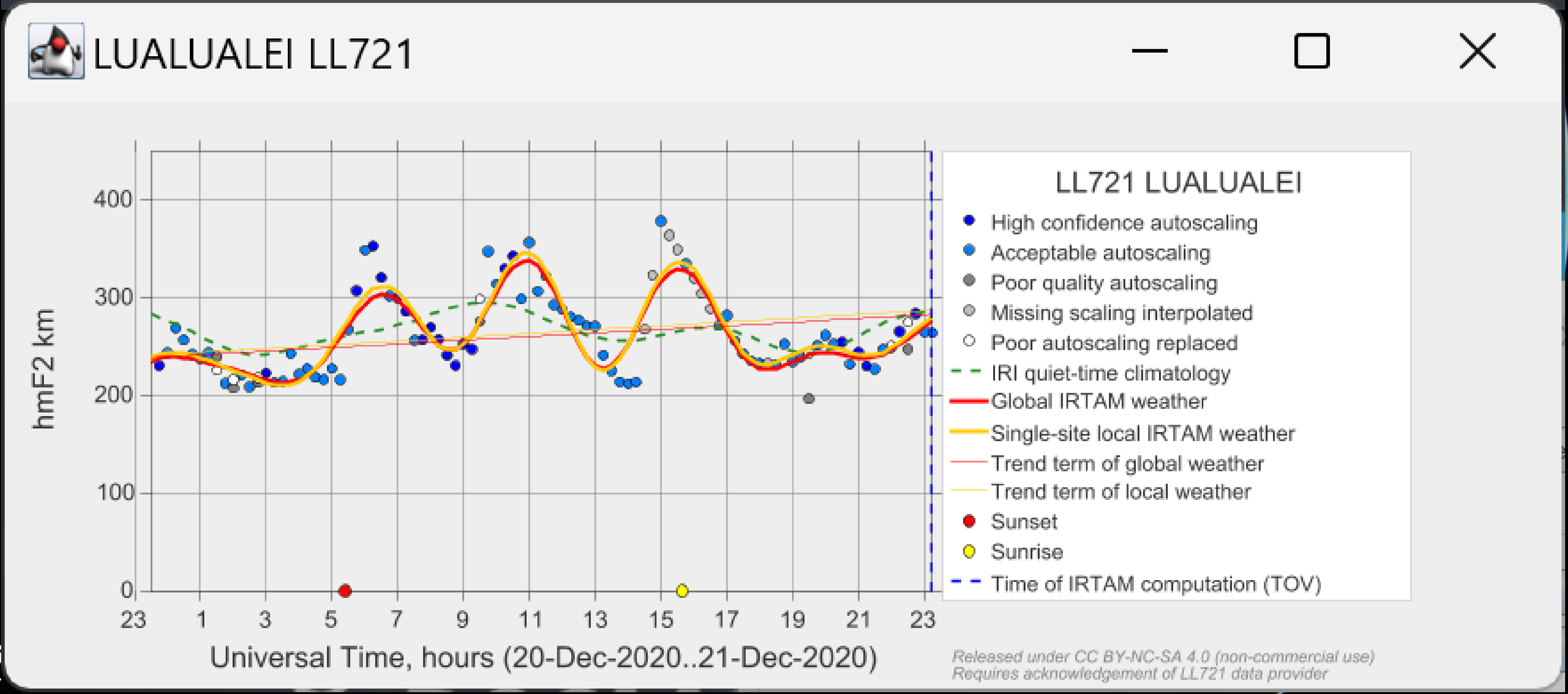
Real-Time IRI Task Force

- Founded in 2009
- Concept: periodically reprocess IRI climate specs of N_e to match available observations
- Two primary objectives:
  - Capture the weather timeline of global ionospheric conditions
    - Build animated *anomaly* maps of deviations from quiet-time conditions
  - Provide weather monitoring capability to applications
- Two aspects:
  - Driving a data-driven empirical model with new data = **Assimilative IRI**
  - Low-latency sensor data streams = **Real-Time IRI**
- **IRTAM = IRI-based Real-Time Assimilative Model**
  - **(One example of the Task Force activity)**

Single station chart of IRI, ionosonde, and IRTAM

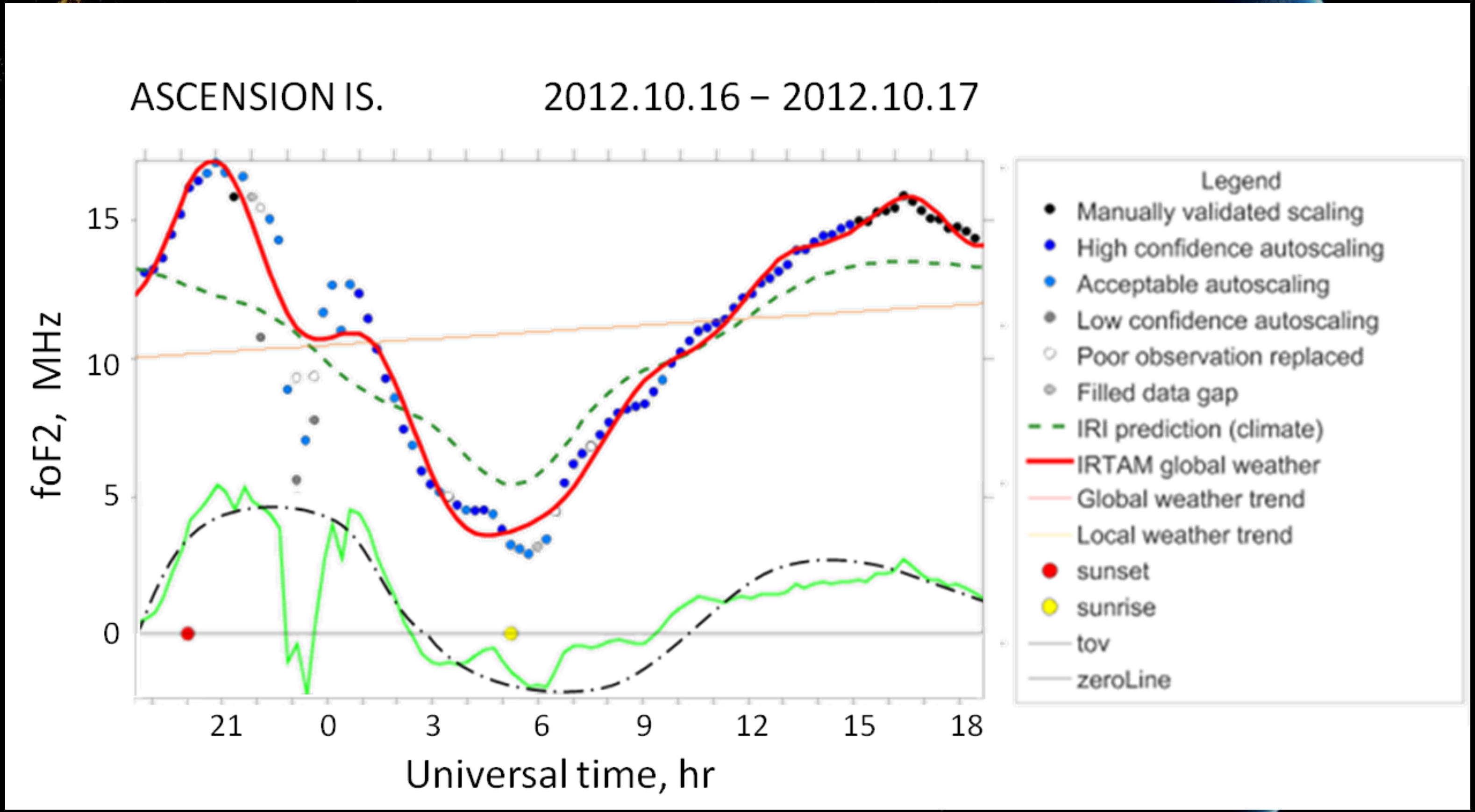
One IRTAM Computation = Red Line, matches 24 hours of data

Available online at https://giro.uml.edu



New to IRTAM: working on attenuation ellipses

- Underlying principle: IRTAM works with diurnal harmonics
- 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?



Principles of IRTAM: NECTAR Technique

NECTAR

- NECTAR is a 24-hour 4DDA algorithm:
  - At each sensor site *k*, use 24-hour history of *deviations* from IRI, Δ_k
  - Expand Δ_k into *j* diurnal harmonics
    - Use the same 6th order Fourier series as in IRI
  - Interpolate-Extrapolate Δ_{kj} to global 2D, individually for each *j*
  - Expand to Jones-Gallett spatial basis *m*
  - Add 998 resulting corrections Δ_{kjm} to 998 original IRI coefficients
  - Twist: Linear-trend term added to IRTAM's diurnal harmonics = total 1024 coeffs
- This is a GRAY BOX approach
  - IRI background is responsible for capturing underlying geophysics with solar, seasonal, and geomagnetic field dependencies
  - IRTAM merely *adjusts* IRI background using Δ_{kjm}
    - IRTAM represents observations faithfully
    - IRTAM gradually returns to background over no-sensor regions

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

GIRO ionosondes only, IRTAM 3D assimilative model

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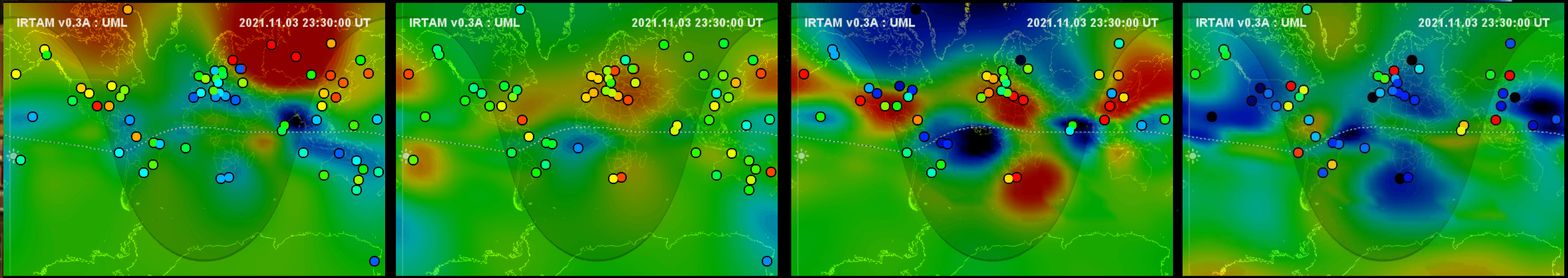
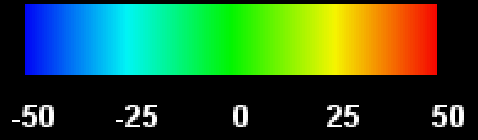
NOT A SIMULATION



Δ foF2 Δ hmF2 Δ B0 Δ B1



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"Anomaly map" = Percent Deviation from Quiet Conditions

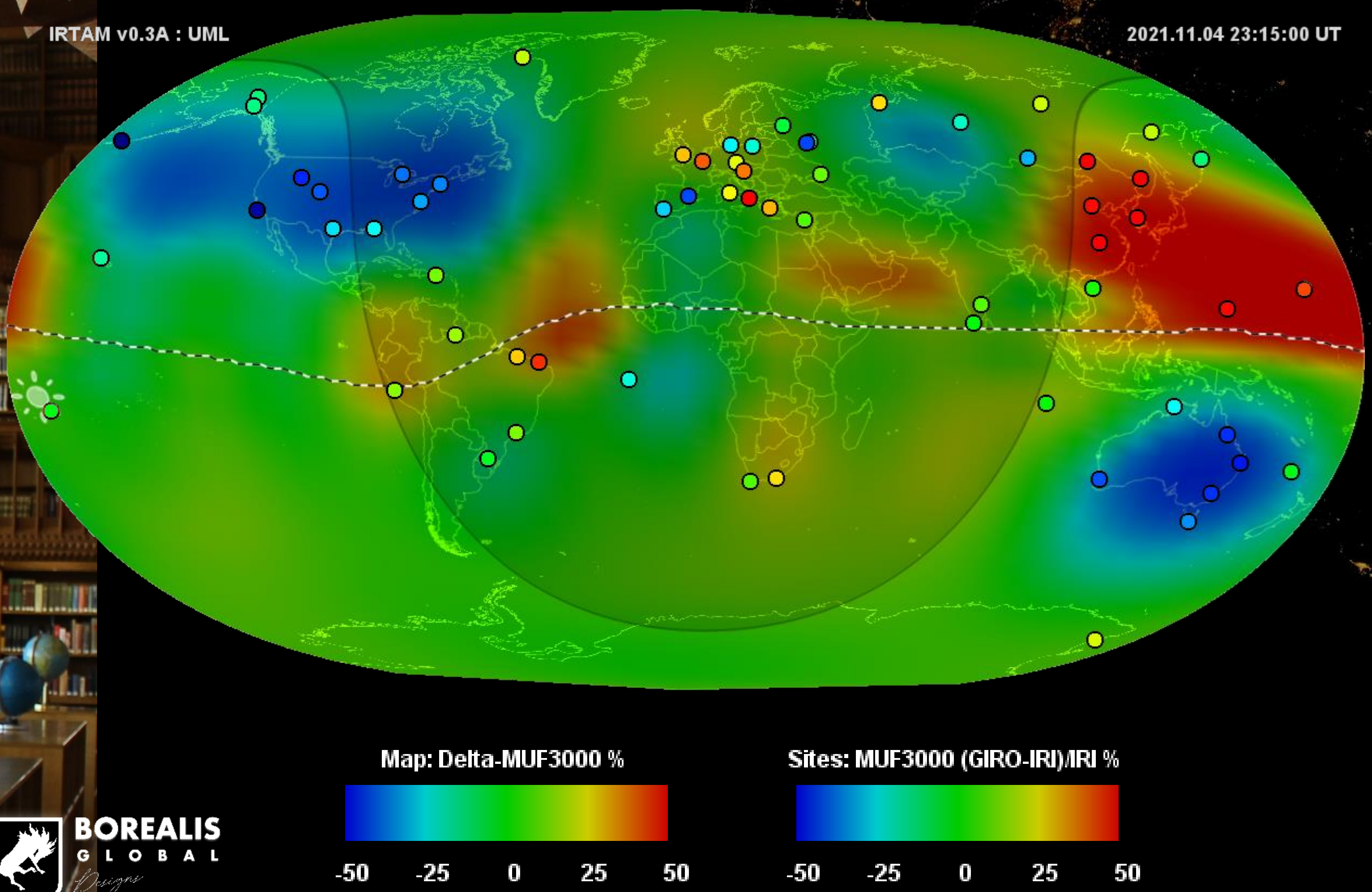
Gambit eXplorer

MUF(3000) weather maps in IRTAM

First attempt at the capability

MUF is maximum usable frequency
3000 refers to a radio link of 3000 km ground distance

MUF(3000) Anomaly Map by IRTAM 3D



- ~75% of the civil aviation route path uses HF for safety messages
  - Especially on transpolar routes
  - HF: high reliability/coverage
  - Unless disturbed ionosphere
- 50% MUF Depression is a severe-level alert
- MUF (D) computation: 3D density model is required

Building MUF(3000) using GIRO

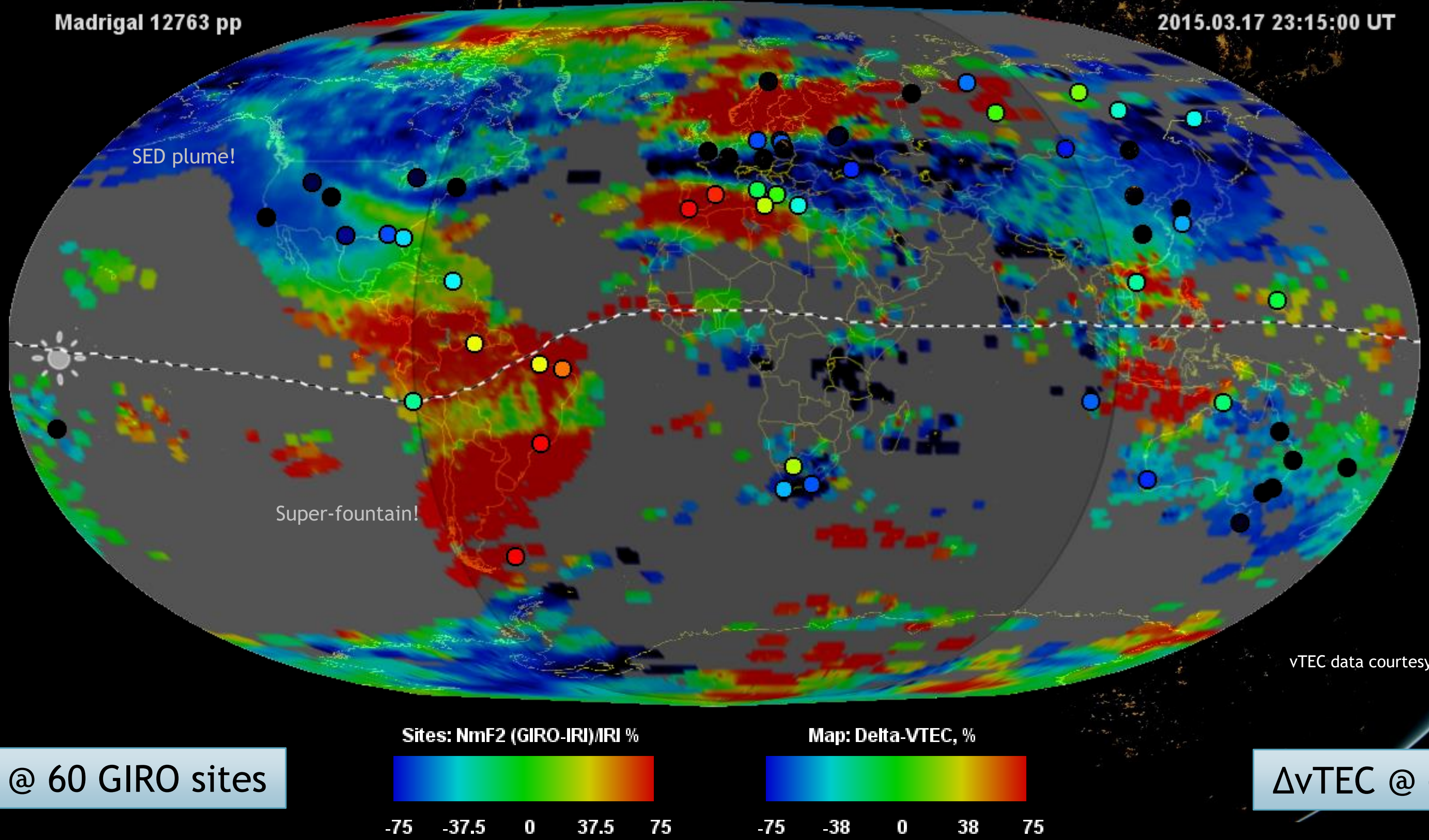
- The expected approach to assimilation:
  - Obtain MUF(3000) observations from GIRO location
  - Build MUF(3000) climate map using IRI
    - M(3000) and foF2 maps are available in IRI
  - Apply NECTAR assimilation algorithm to compute the weather map of MUF(3000)
- Currently implemented, simpler approach
  - Obtain weather maps of foF2 and hmF2 from IRTAM
  - Apply empirical formula for hmF2 in the reverse direction to obtain M(3000)
  - Compute MUF(3000) from M(3000)
- Building MUF(3000) maps from foF2 and hmF2 has its merits
  - Allows contributions from other sensors such as RO
- Todo: implement assimilation of GIRO measurements of MUF(3000)

Cooperation of IRTAM and GIM Communities

GNSS and GIRO Data fusion

Prelude: Anomaly maps by IGS and GIRO networks

St. Patrick storm
March 17, 2015 23:15



Gambit eXplorer
giro.uml.edu/GAMBIT

vTEC data courtesy MIT Haystack Madrigal Repository

ΔNmF2 @ 60 GIRO sites

ΔvTEC @ 6342 GNSS sites

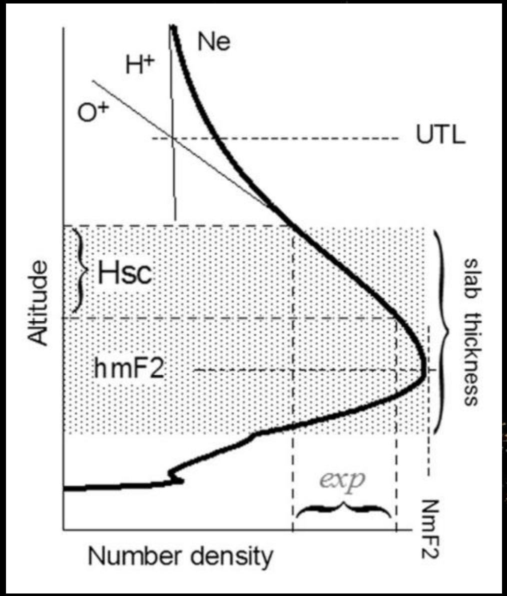
Cooperation of GNSS and GIRO

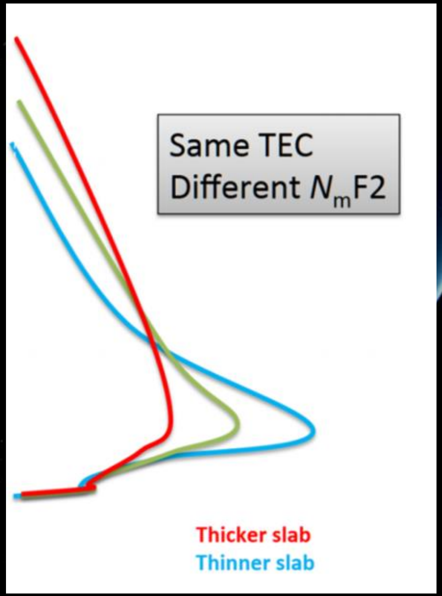
OTHERS:

- 2D: use observed ΔvTEC to derive corrections to NmF2 over no-coverage areas
  - T. Gulyaeva et al.
  - A. Pignalberi et al.
- Assimilate GIRO and GNSS data simultaneously in a 3D model
  - 6000 vs 60 problem
    - GIRO input is insignificant
  - GPSII: weighted assimilation
    - Fridman *et al.*, NWRA/HFGeo

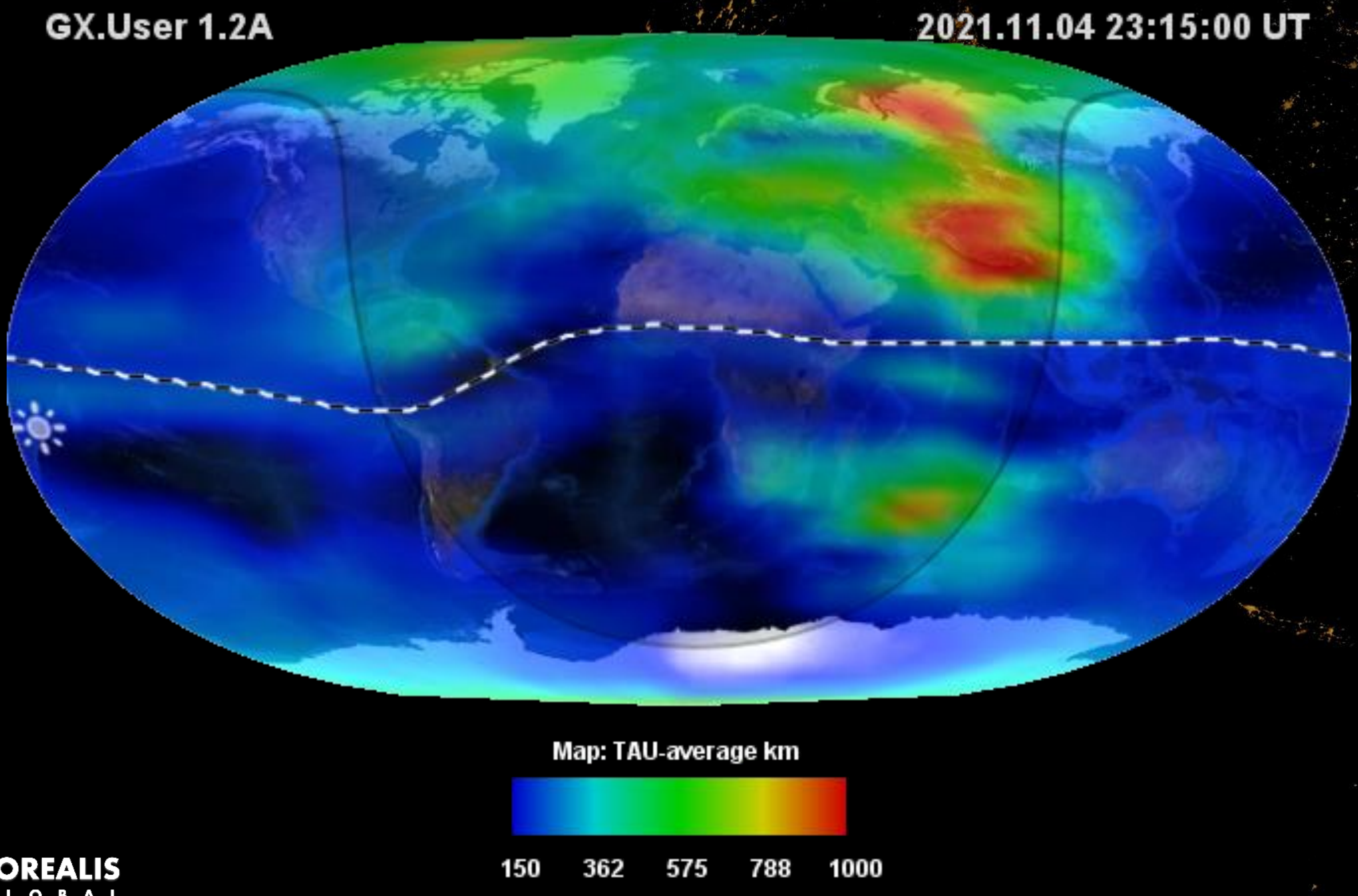
THIS WORK:

- DATA FUSION PROJECT
  - Combine NmF2 and vTEC measurements to reason about slab thickness τ





Slab Thickness Climatology

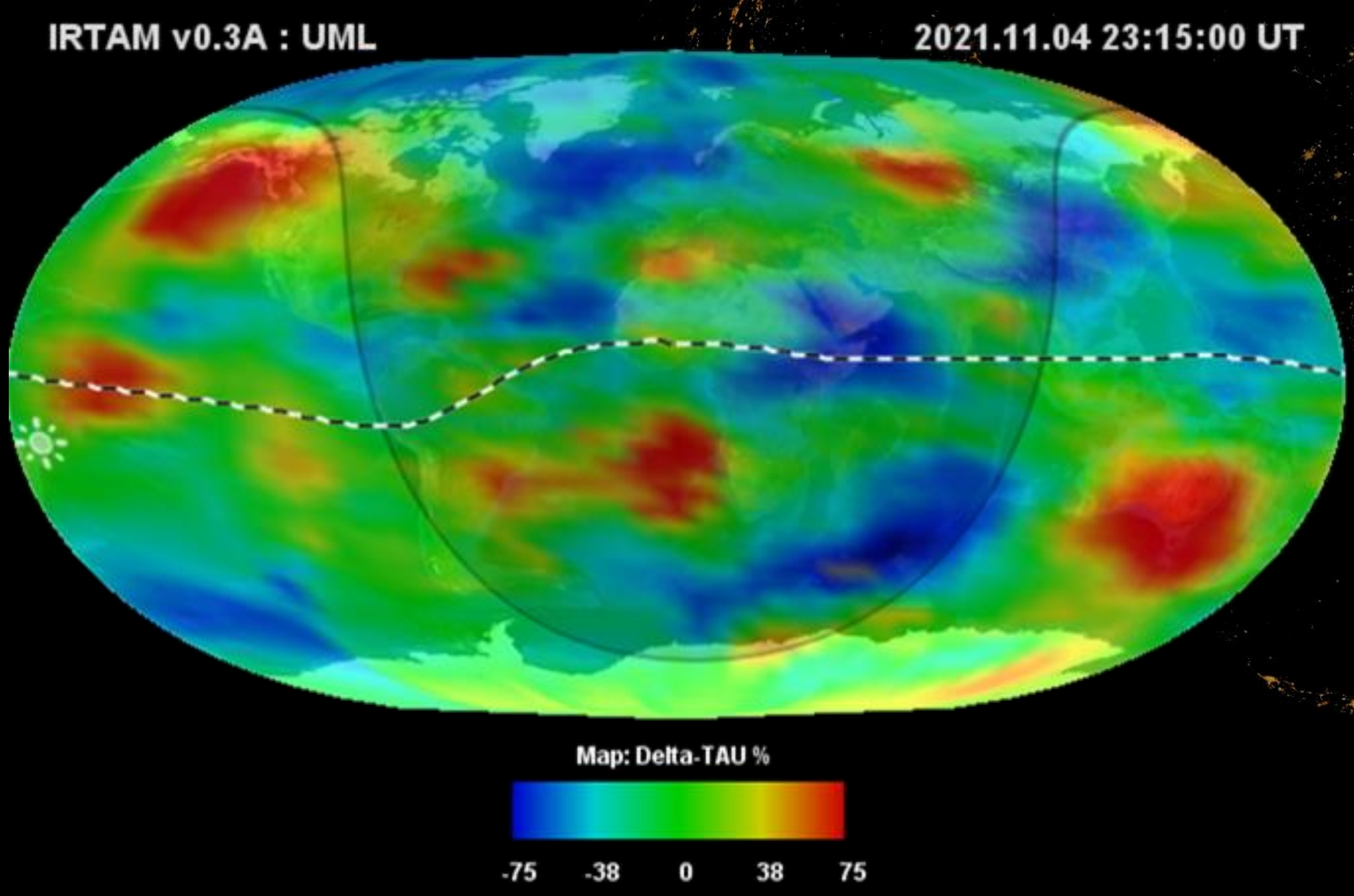


NmF2: IRI foF2 model (climate)
VTEC: IGS 30-day median VTEC

[Fron *et al.*, 2020]

Slab Thickness *Anomaly* Map

2021 Nov 04 storm example



NmF2: IRTAM NmF2 weather
VTEC: IGS VTEC Weather

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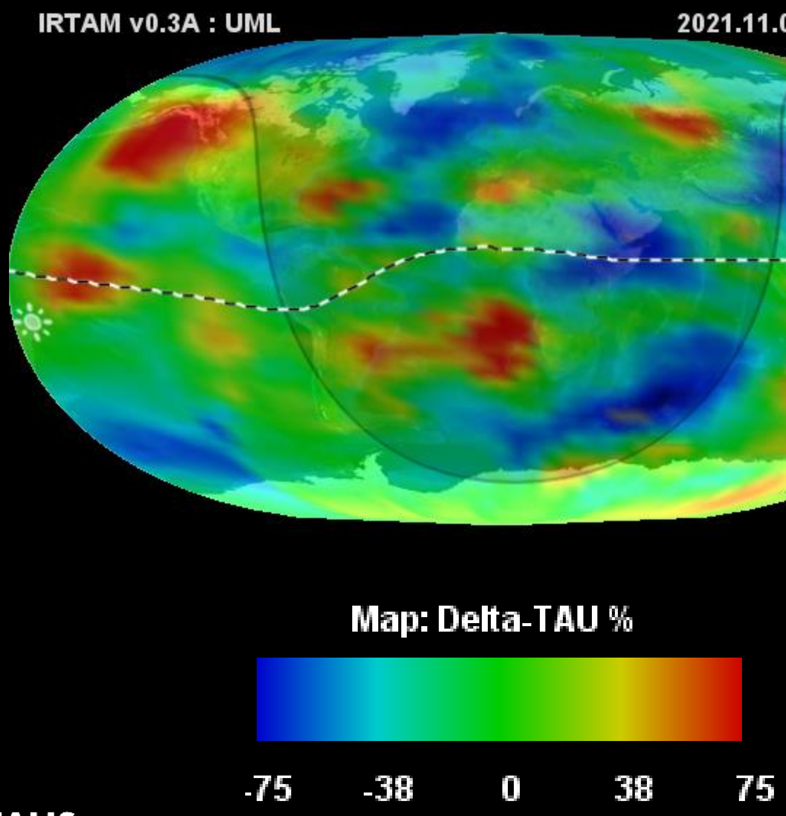
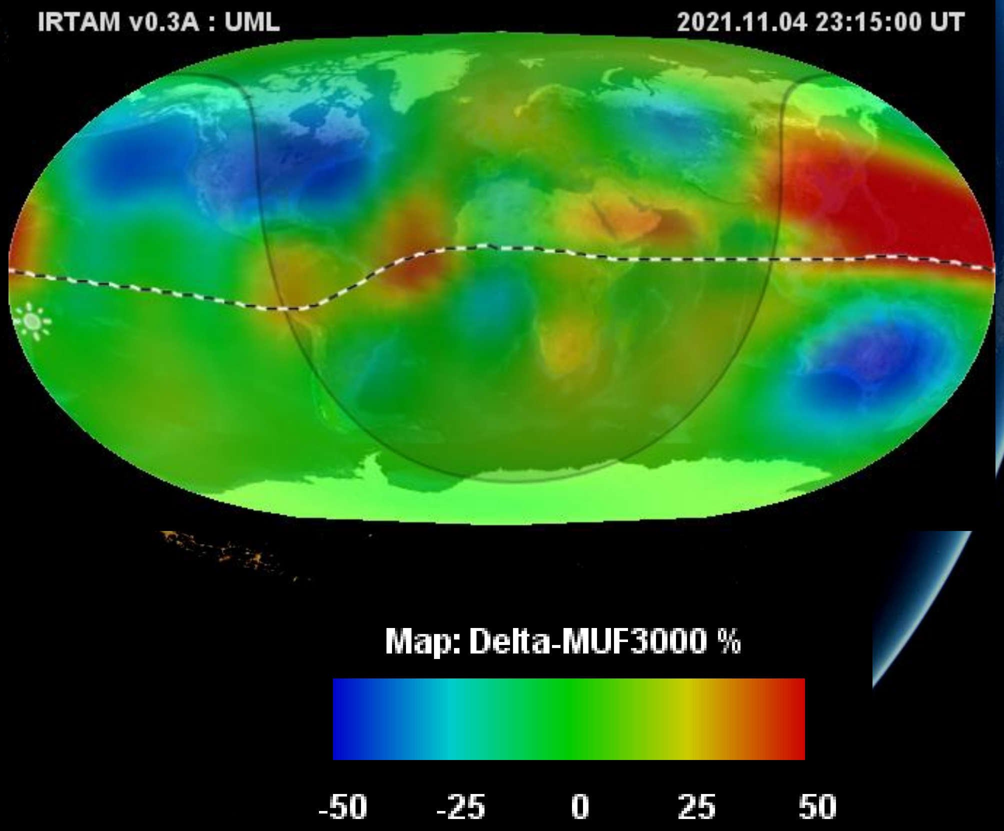
Tau-anomaly vs MUF anomaly (storm-time)

$\Delta\tau$



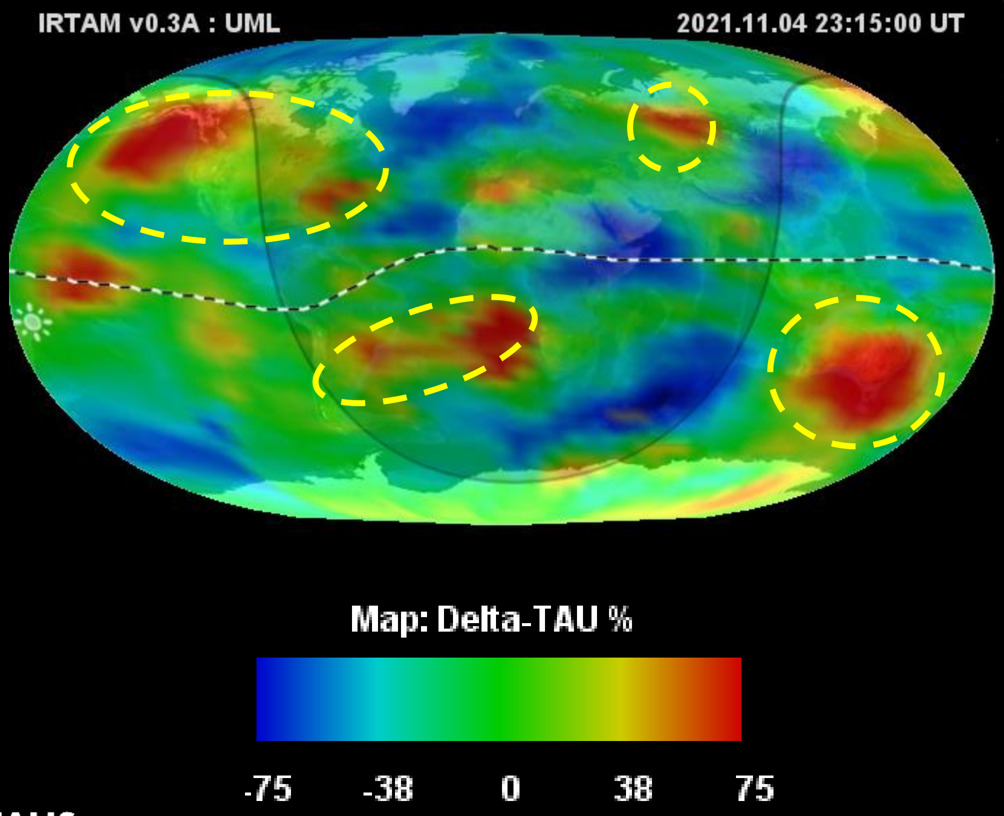
ΔMUF

No VTEC



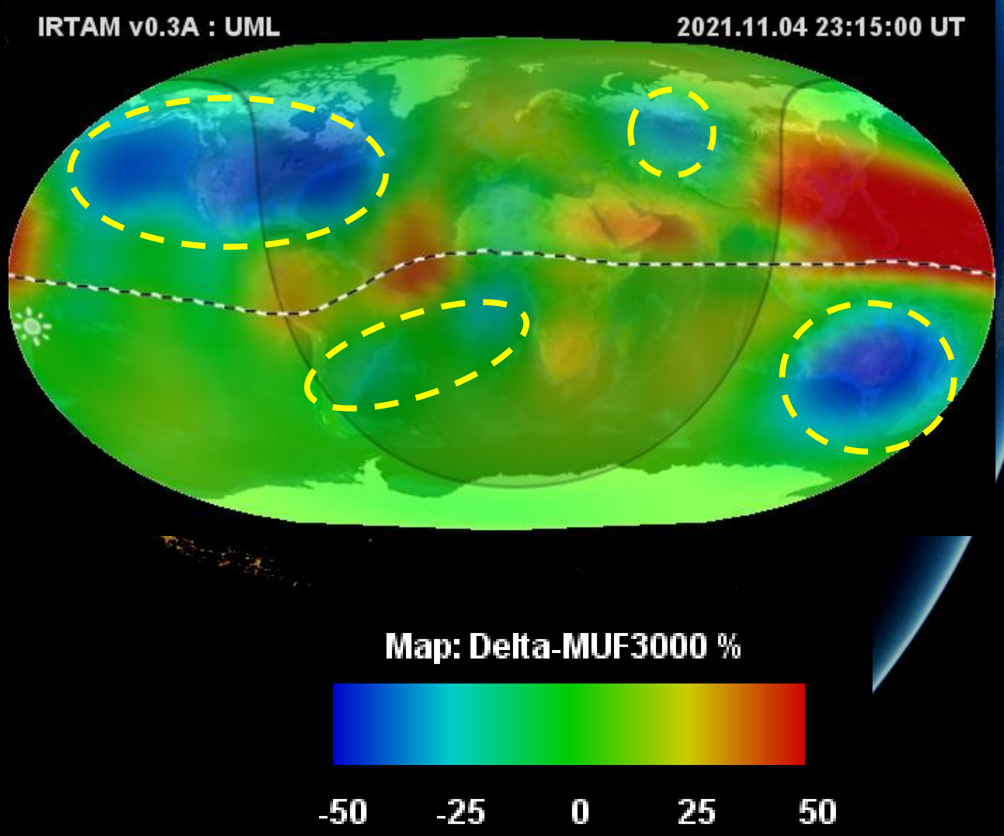
Depressed storm-time MUF

$\Delta\tau$



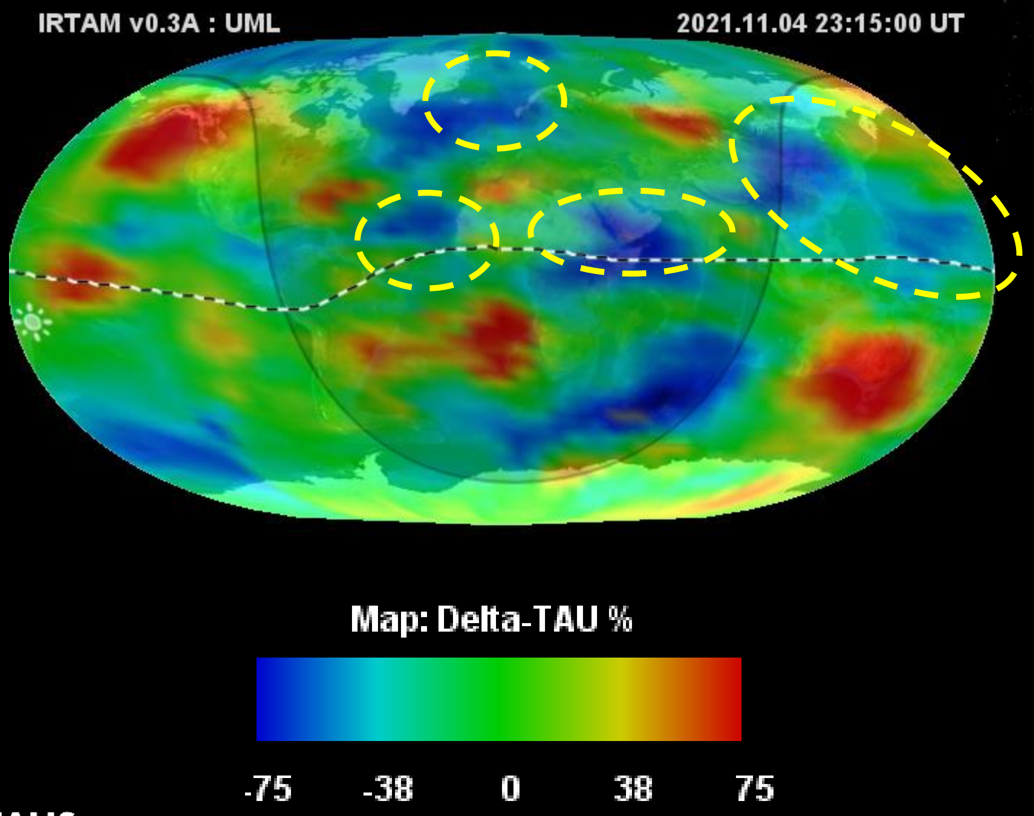
ΔMUF

No VTEC



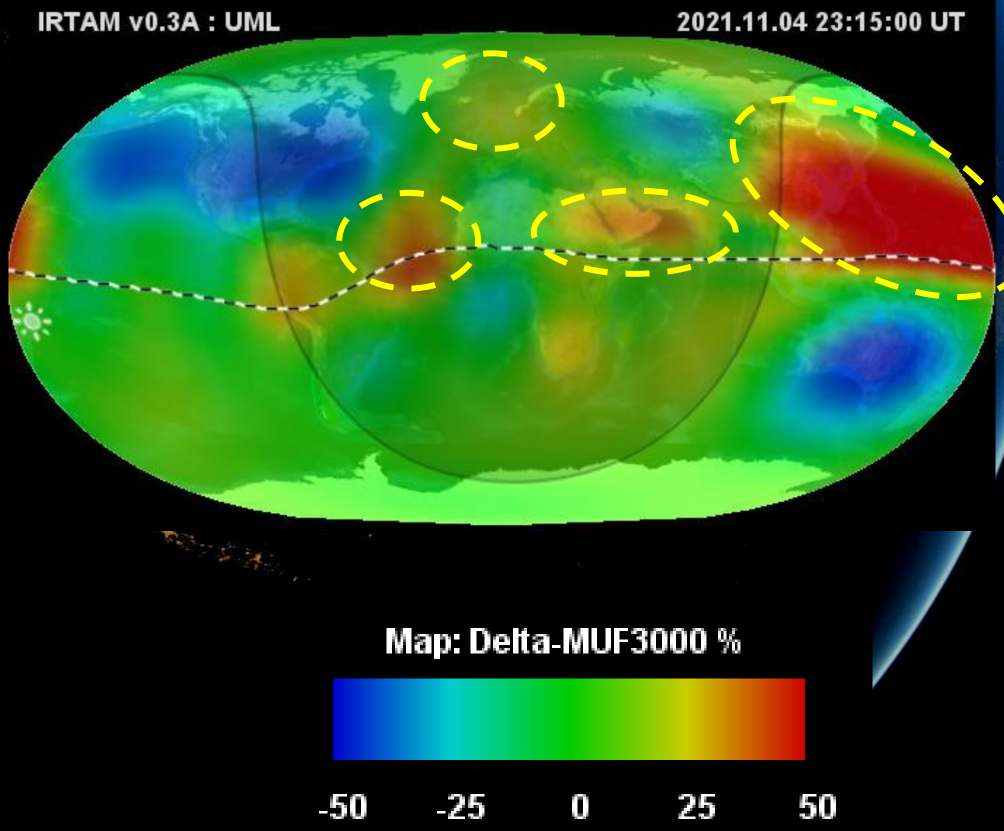
Increased storm-time MUF

$\Delta\tau$



ΔMUF

No VTEC



IRTAM Open Problems

- Need to complete fusion with near-real-time global VTEC maps (GIMs)
  - Work with IGS Coordination Center at UWM Olztyn
- ELO (Elastic Linear Optimizatioin): capability
  - Assimilate sensor data from moving platforms such as COSMIC/SPIRE
  - 4DDA technique to analyze 24-hour history of RO data
  - Similar *Model Morphing* approach as in NECTAR
- h_mF2 dilemma in IRTAM: did not fare well in comparisons to COSMIC h_mF2 data
  - Possibly related to the IRTAM using IRI-2000 background climate specification of h_mF2
  - Upgrade IRTAM to Shubin *et al*. background model of h_mF2 from IRI 2020
  - Rerun comparisons to COSMIC/RO h_mF2
- Optimize attenuation trajectories (AUROC investigation)
- Improve MUF(3000) weather mapping algorithm by involving ionosonde data
- Increase expansion orders in IRTAM?
  - Capture finer detail
  - Improve "underestimation" problem due to smoothing artifacts
- Assimilate VTEC in IRTAM?
- Ingest WDC/SPIDR ionosonde archives into DIDBase, rerun IRTAM?

hmF2 in IRTAM: improve layer liftup representation