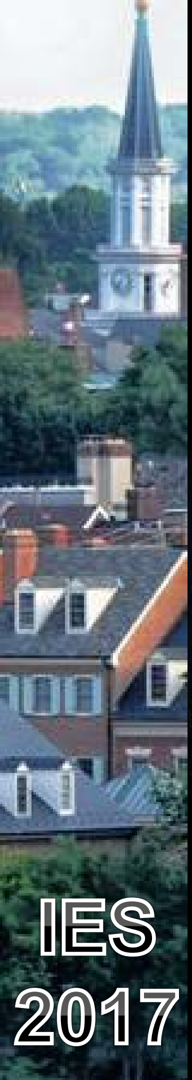

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Bodo Reinisch[1,2]
Xueqin Huang[2]
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REALISTIC IONOSPHERE

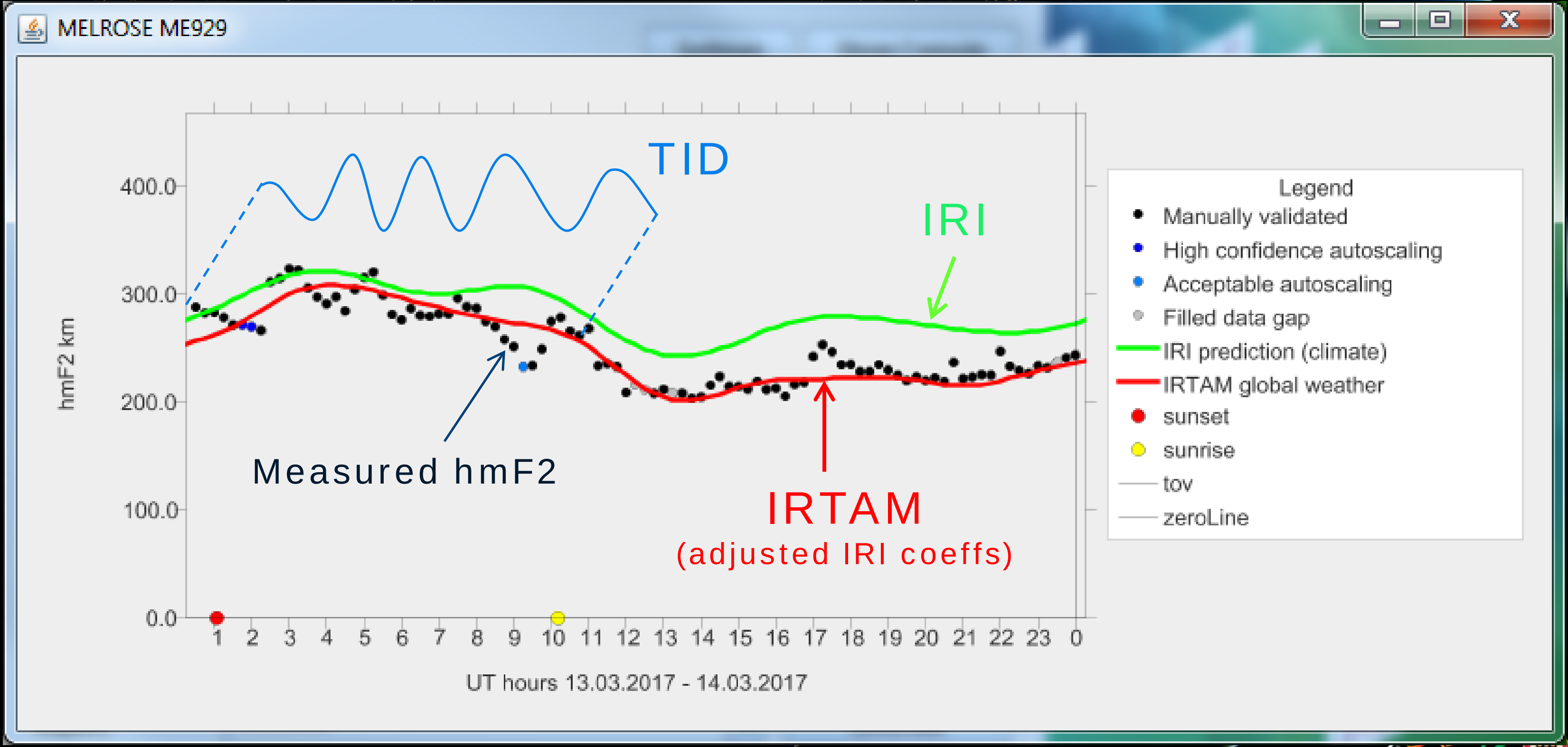
Specification in Support of a TID Warning System

15th International Ionospheric Effects Symposium
Alexandria • Virginia • May 9-11, 2017
Session 2a | HF Modeling, TIDs, and Geolocation

Outline

- Realistic Ionosphere Concept
- IRTAM: Assimilation Techniques for Real-Time IRI
  - GIRO (ground-based) V0.2 – close to V1.0 release
  - Moving platform extension – encouraging early results from ELO
- TID Explorer
  - Frequency-Angular Sounding (FAS)
  - Digisonde-to-Digisonde (D2D) sounding with HF pulses
- RayTRIX: Raytracing through Realistic Ionosphere eXplorer
  - Based on HR2006 Raytracing code
  - Offline testing results available
- TID Warning system: transition to fully autonomous operation
  - Intelligent systems for RI

Realistic Ionosphere: IRTAM+TIDx



Digisonde data courtesy of Robert Moore, Florida University

IES 2017

VA ● May 9, 2017
Modeling, TIDs, and Geolocation

Realistic Ionosphere Implementation

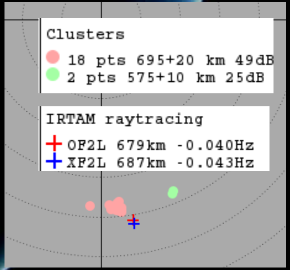
foF2, hmF2, B0. B1 → **IRTAM** → 3D smooth subpeak weather → **RayTRIX**

GIRO ionosondes

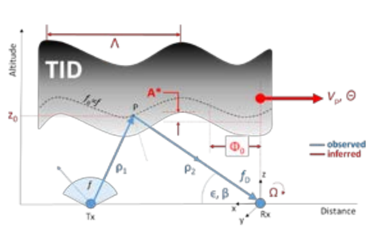
IRI → **IRTAM**

D2D Spectra (oblique sounding) → **TID Explorer** → TID detections → **RayTRIX**

RayTRIX → Raytracing products



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



SSL UML SPACE SCIENCE LAB
LDI

Realistic Ionosphere = IRTAM + TID + RayRTIX

1. IRI-based Real-Time Assimilative Model

1A. IRTAM driven by GIRO (ground-based network of ionosondes)

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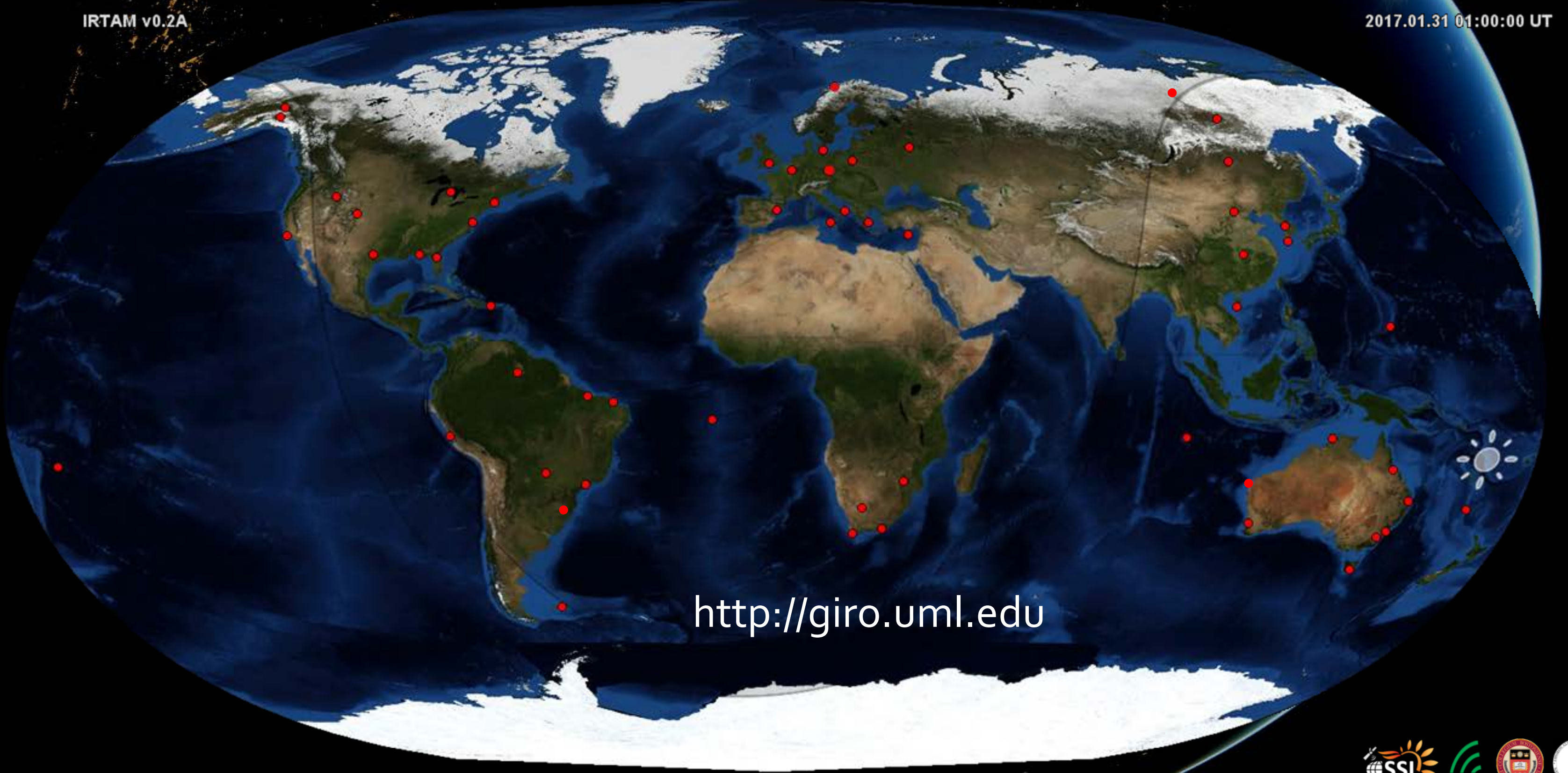
Global Ionosphere Radio Observatory

Real-time GIRO ionosondes, ~60 RT locations



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Session 1a | HF Modeling, TIDs, and Geolocation

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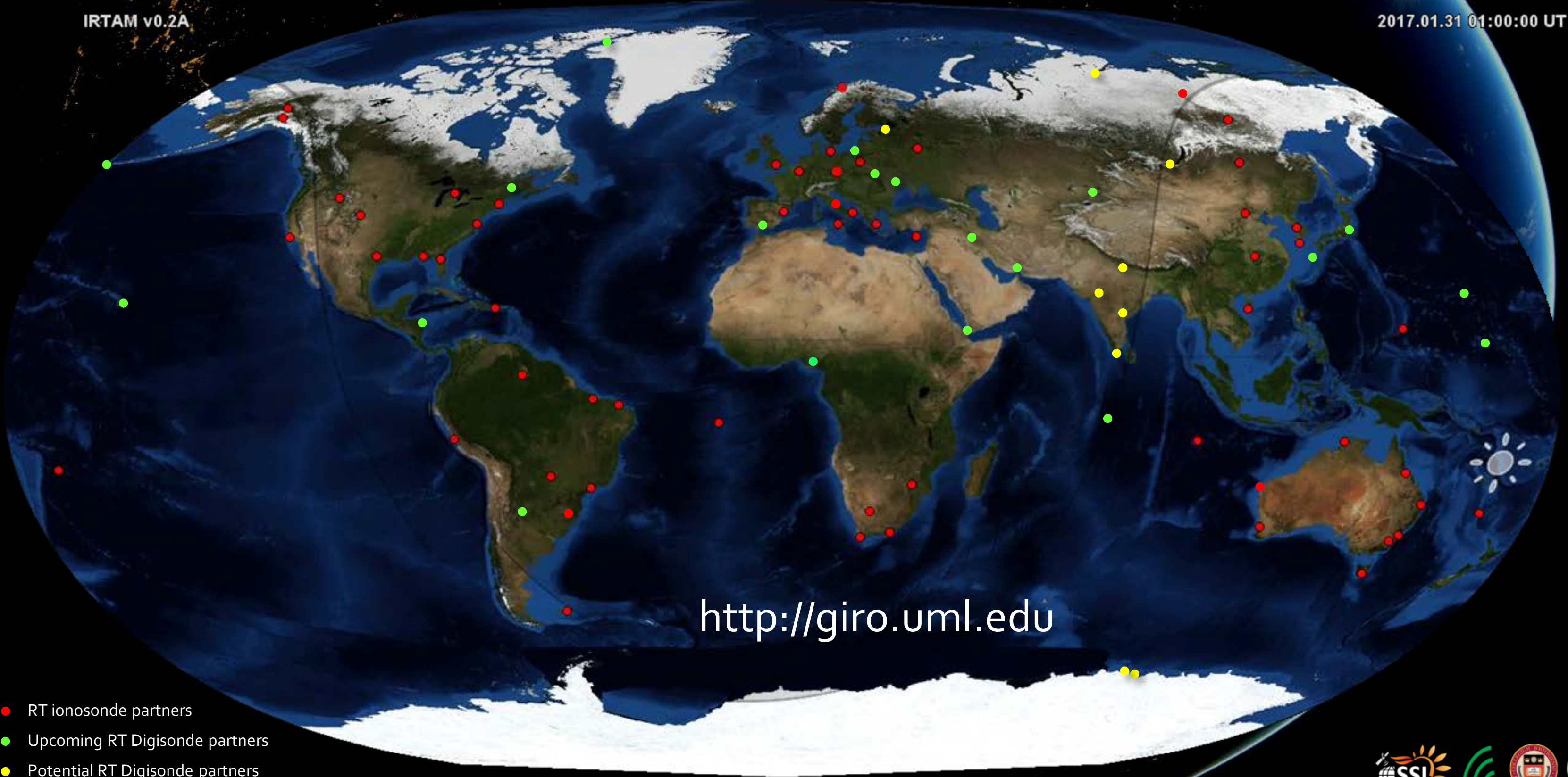
Global Ionosphere Radio Observatory

Real-time GIRO ionosondes, ~60 RT locations + upcoming RT locations



- RT ionosonde partners
- Upcoming RT Digisonde partners
- Potential RT Digisonde partners

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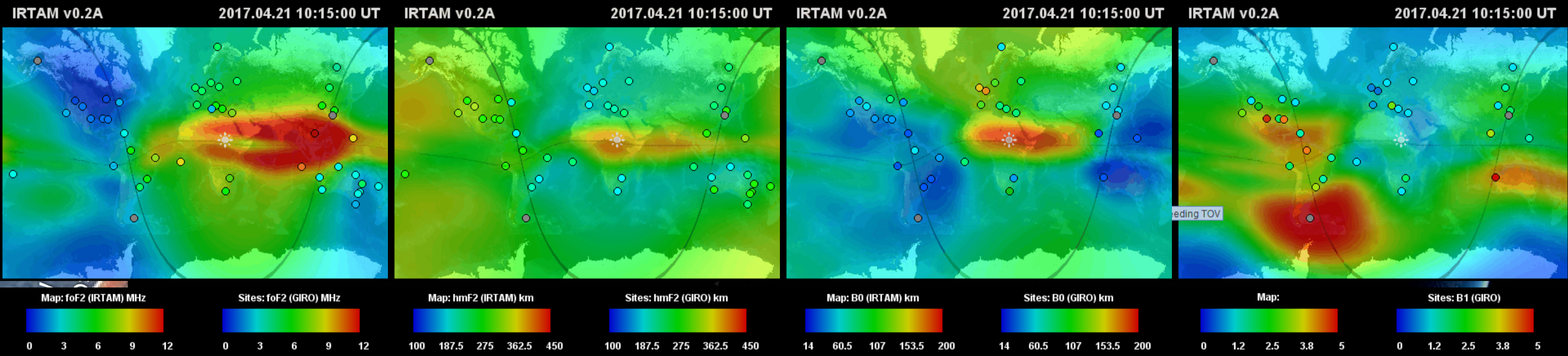
IRTAM 24-hour Animations

NECTAR



$f_o F2$ $h_m F2$ $B0$ $B1$

Used as input drivers to IRI density profile for 3D specification

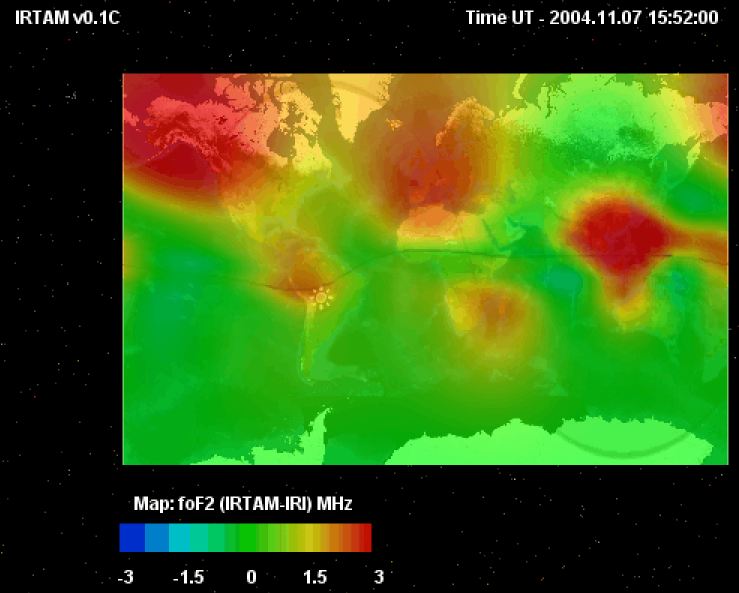
Alexandria, VA
Session 1a | HF Model

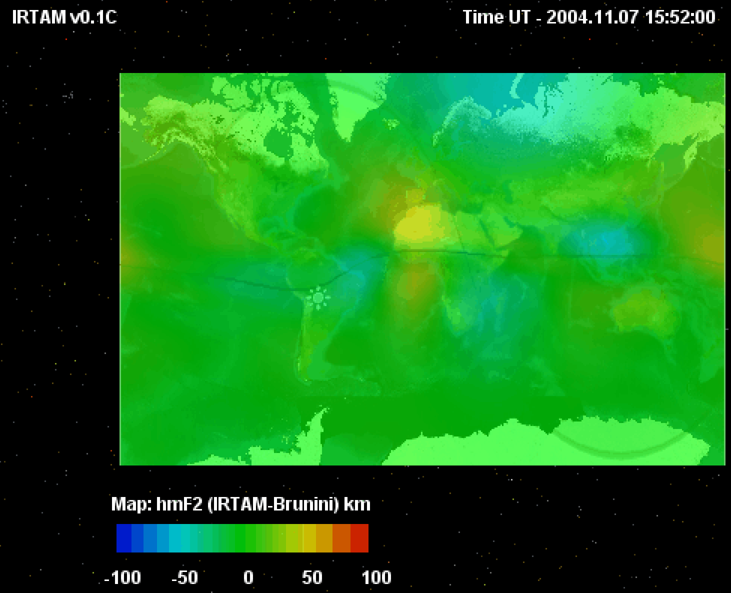
IES 2017

IRTAM Deviation Maps

HOW IONOSPHERE IS DIFFERENT FROM ITS QUIET-TIME STATE

Global Nowcast





$\Delta f_o F2$

Is this real?

$\Delta h_m F2$

Alexandria , VA • May 9, 2017

Session 1a

IRTAM Solutions to AM Challenges

- Spatial prediction in areas of no GIRO coverage
  - Not interpolation/extrapolation of hmF2
  - Not interpolation/extrapolation of ΔhmF2 ("measurement – model" deviations)
  - Interpolation/extrapolation of diurnal harmonics of ΔhmF2
- Diurnal harmonics of Δ are determined first
  - 24-hour previous history of Δ is evaluated at each GIRO site
- Each harmonic is expanded into its own spatial basis
- No propagation of update step to forecast step
  - Each update step is restarted with new sliding 24-hour windows

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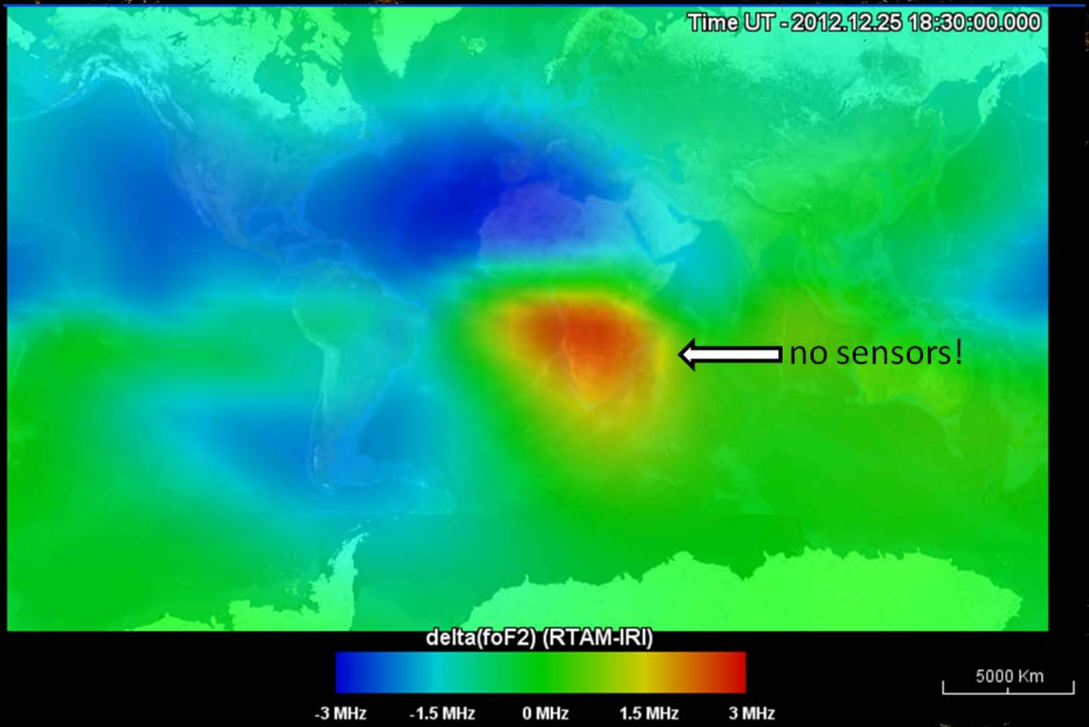
Session 1a | HF Modeling, TIDs, and Geolocation

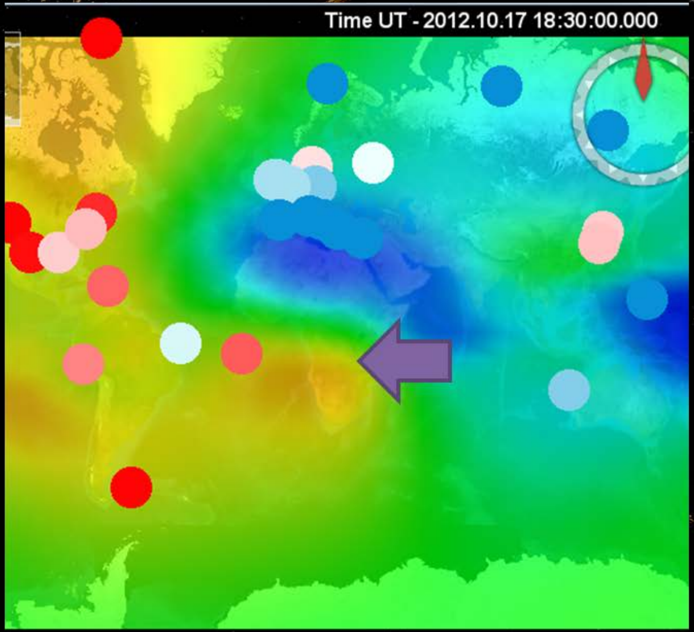
Curious Predictive Capability, TBR



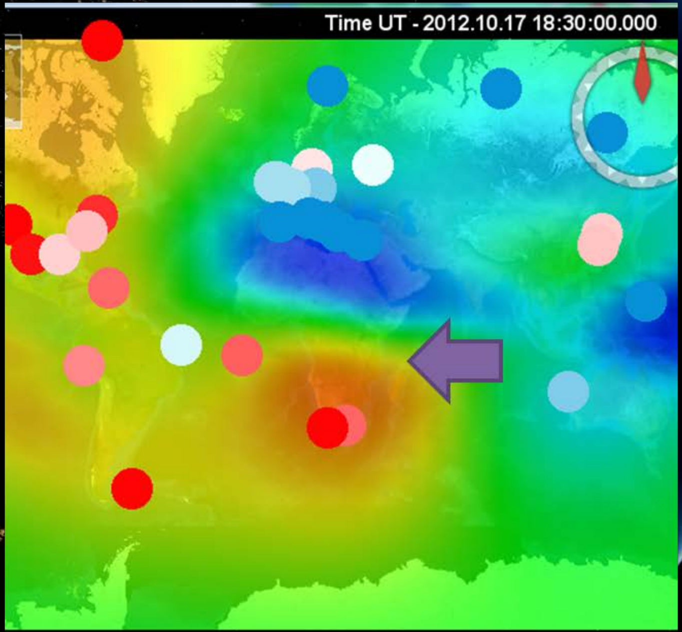
Red spot over Africa

Red-spot Validation

with South African measurements



RSA data excluded



RSA data included

RSA data courtesy of Lee-Anne McKinnel, SANSA

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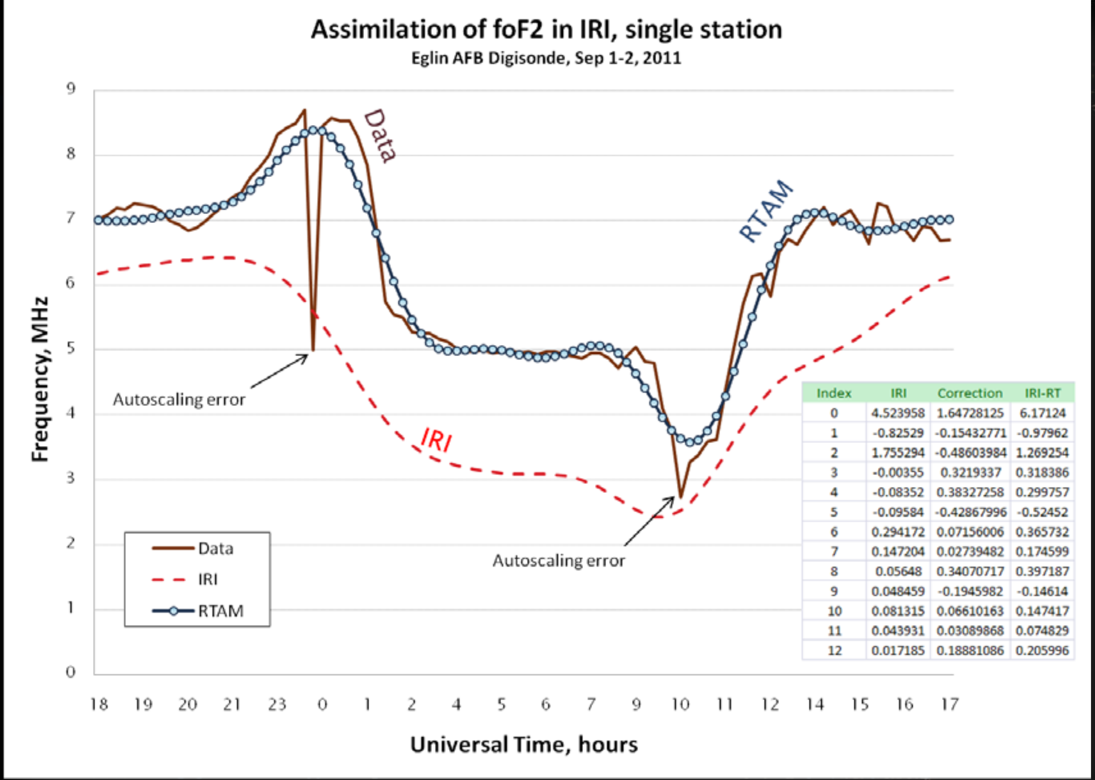
24-hour Diurnal Harmonics Expansion

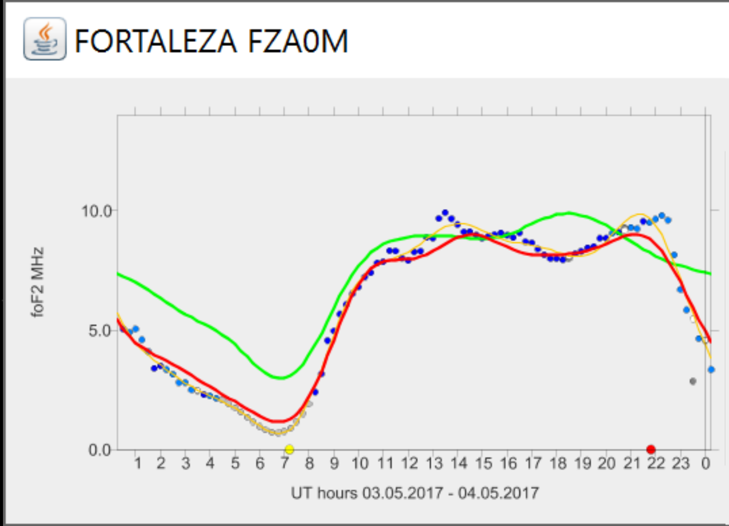
4DDA approach is robust to autoscaling blunders

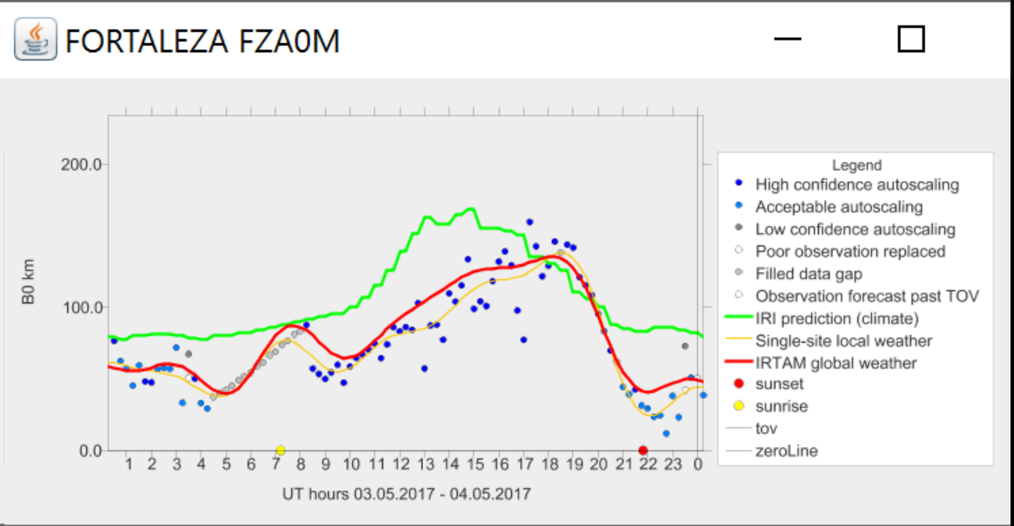


Index	IRI	Correction	IRI-RT
0	4.523958	1.64728125	6.17124
1	-0.82529	-0.15432771	-0.97962
2	1.755294	-0.48603984	1.269254
3	-0.00355	0.3219337	0.318386
4	-0.08352	0.38327258	0.299757
5	-0.09584	-0.42867996	-0.52452
6	0.294172	0.07156006	0.365732
7	0.147204	0.02739482	0.174599
8	0.05648	0.34070717	0.397187
9	0.048459	-0.1945982	-0.14614
10	0.081315	0.06610163	0.147417
11	0.043931	0.03089868	0.074829
12	0.017185	0.18881086	0.205996

Eglin AFB foF2 measurements courtesy USAF NEXION program

Autoscaling Jitter Protection



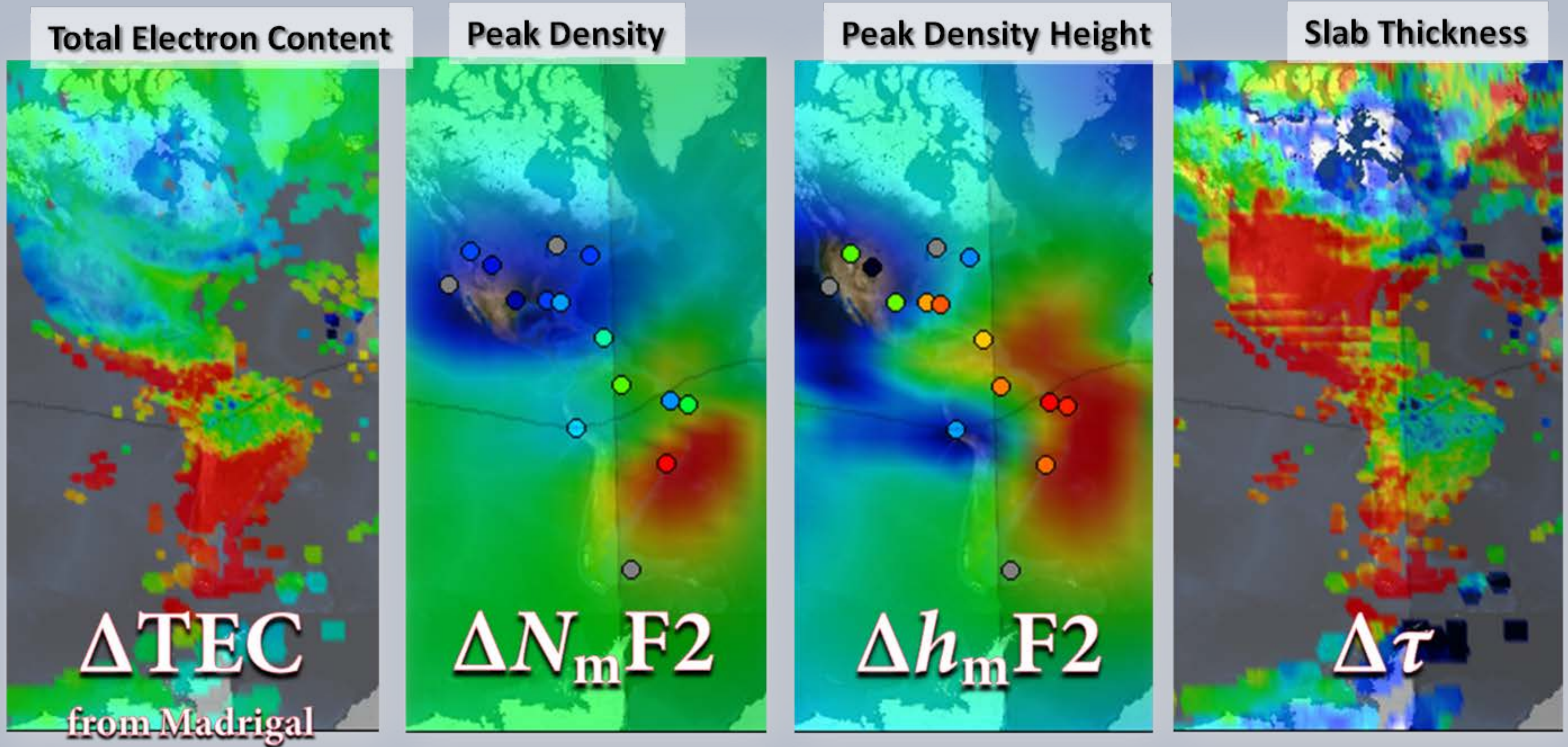


foF2 (no jitter)

B0

Fortaleza DPS4D measurements courtesy Inez Batista, INPE, Brazil

IRTAM complementary to TEC maps



Deviation from expected quiet-time behavior

Red: larger than model   Blue: smaller than model

Substorm March 17, 2015 23:22UT

TEC maps courtesy Madrigal @ MIT Haystack Observatory; [Coster *et al.*, 2008]

Realistic Ionosphere = IRTAM + TID + RayRTIX

1. IRI-based Real-Time Assimilative Model

1B. IRTAM Extension for moving platform data (space-based sensors)

Assimilating Data from Moving Platforms

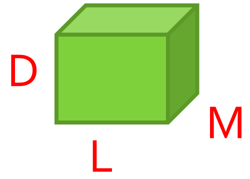
- Occasional fly-bys
- No means to determine diurnal harmonics
- Vernier Scale of IRTAM technologies
  - Elastic Linear Optimization Method
    - Enlarging the expansion basis order/degree to capture finer detail than IRI
    - Iterative manipulation of coefficients, in groups, to accomplish the fit

Elastic Linear Optimization (iterative)

Diurnal Expansion

$$F_i^{(T)},\ i \in [0,\ 2I]$$

$$P(T,\varphi,\lambda) = F_0^{(T)} a_0(\varphi,\lambda) + \sum_{i=1}^{I} \left[F_{2i-1}^{(T)} a_{2i-1}(\varphi,\lambda)\sin(iT) + F_{2i}^{(T)} a_{2i}(\varphi,\lambda)\cos(iT) \right]$$



Geographic (Zonal) Expansion

$$F_j^{(L)},\ j \in [0,\ 2J]$$

$$P(T,\varphi,\lambda) = F_0^{(L)} b_0(T,\chi) + \sum_{j=1}^{J} \left[F_{2j-1}^{(L)} b_{2j-1}(T,\chi)\sin(j\varphi)\cos^j \lambda + F_{2j}^{(L)} b_{2j}(T,\chi)\cos(j\varphi)\cos^j \lambda \right]$$

Geomagentic (Meridional) Expansion

$$F_k^{(M)},\ k \in [0,\ K]$$

$$P(T,\varphi,\lambda) = \sum_{k=0}^{K} F_k^{(M)} c_k(T,\varphi,\lambda)\sin^k \chi$$

F factors are linear modifiers of the coefficients in groups, ensuring *elastic*, constrained transformation of the model

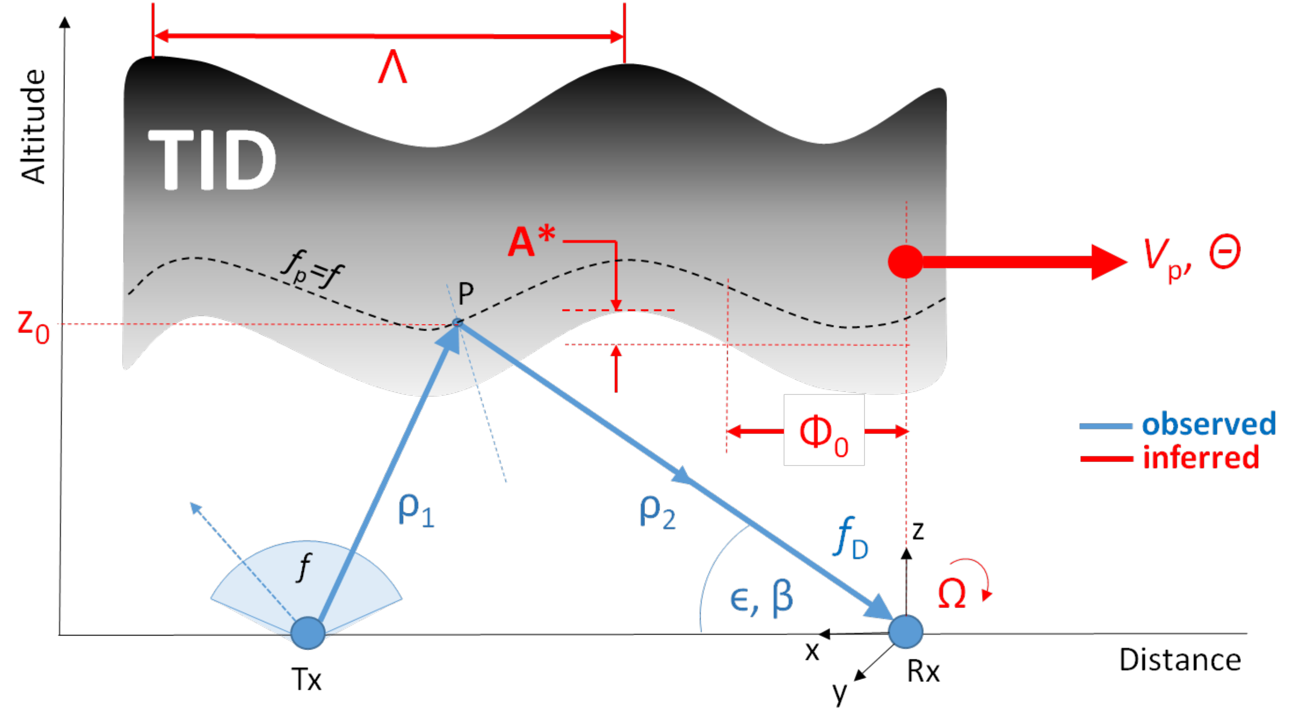
Realistic Ionosphere = IRTAM + TID + RayRTIX

2. Traveling Ionospheric Disturbances:
Detection and evaluation

TID Evaluation using D2D and FAS

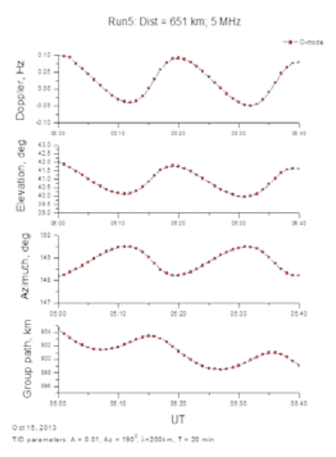
HF Pulsed sounding for multi-path resolution

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



FAS and SAF

2 x 1 km UTR-2 phased array



- **Frequency and Angular Sounding (FAS):**
  - **1995: initial results from the FAS team at RIAN [Beley, Galushko, Yampolsky]**
  - **2012: Implemented in Digisonde [Paznukhov *et al.*] for ground-based HF power beacons**
  - **2017: Implemented in European Net-TIDE project for D2D links [Reinisch *et al.*]**
- **Synthesis of Angles and Frequency (SAF):**
  - **2016: Simulated variations of angles/frequency [Huang *et al.*]**
    - **Required precision of angle measurements ~1°**
    - **Required signal-to-noise ratio (SNR) is 30-40 dB**
    - **Unprecedented fidelity of Digisonde operations needed**

European Net-TIDE Project

presented earlier today in 1A session

Alexandria , VA ● May 9, 2017

Session 1a | HF Modeling, TIDs, and Geolocation

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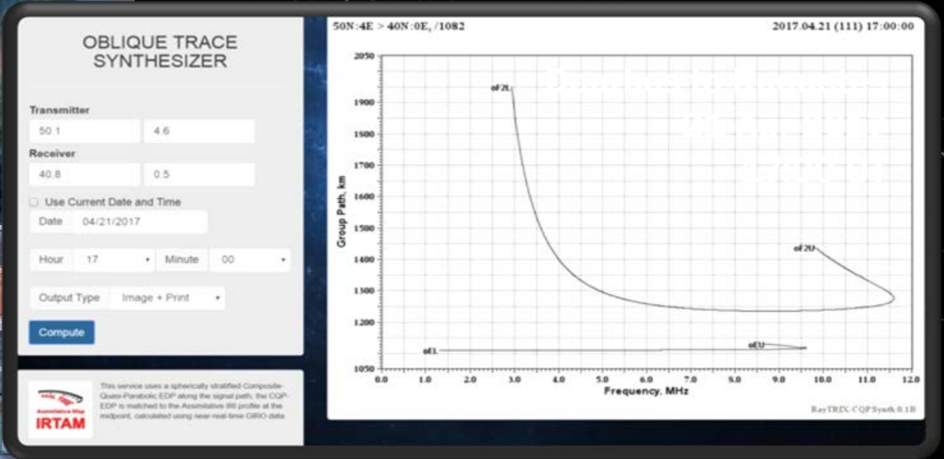
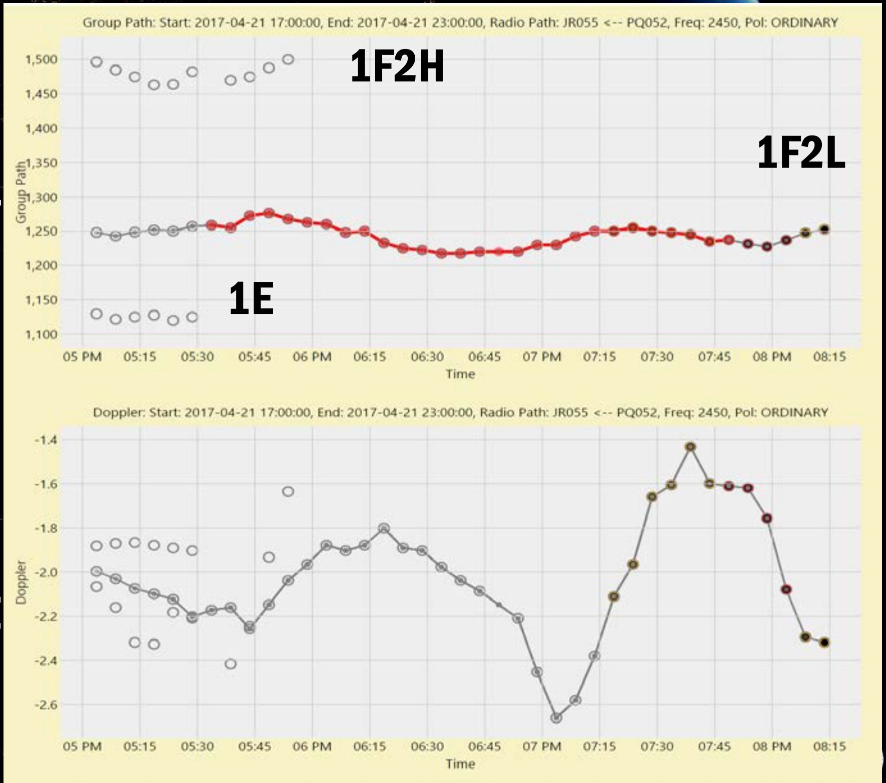
“EGU Opening” TID: April 21, 2017 19:00 UT

Dourbes to Roquetes link (1082 km)

Multi-path separation at work





15% TID, 410 m/s

2500 km, 100 min

245° azimuth CW

Accuracy sufficient for a warning system

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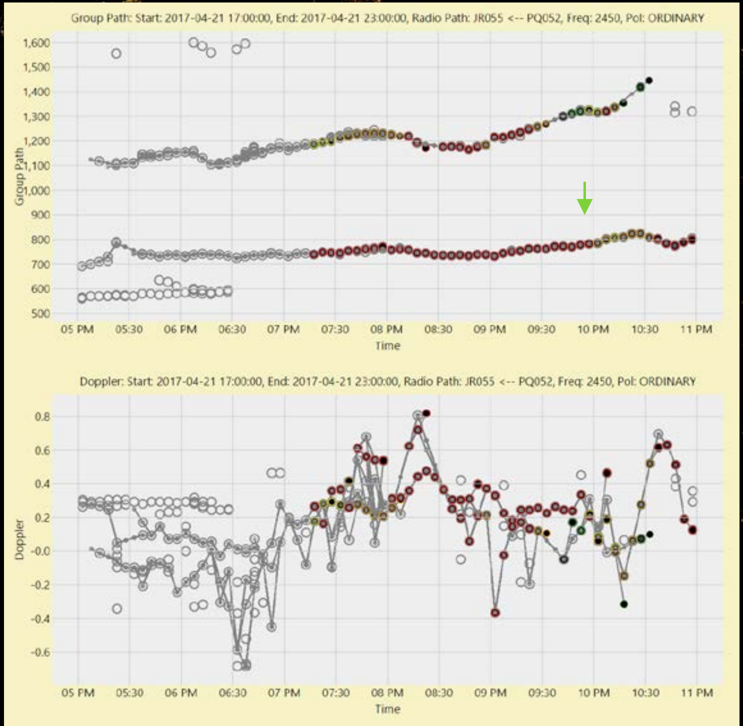
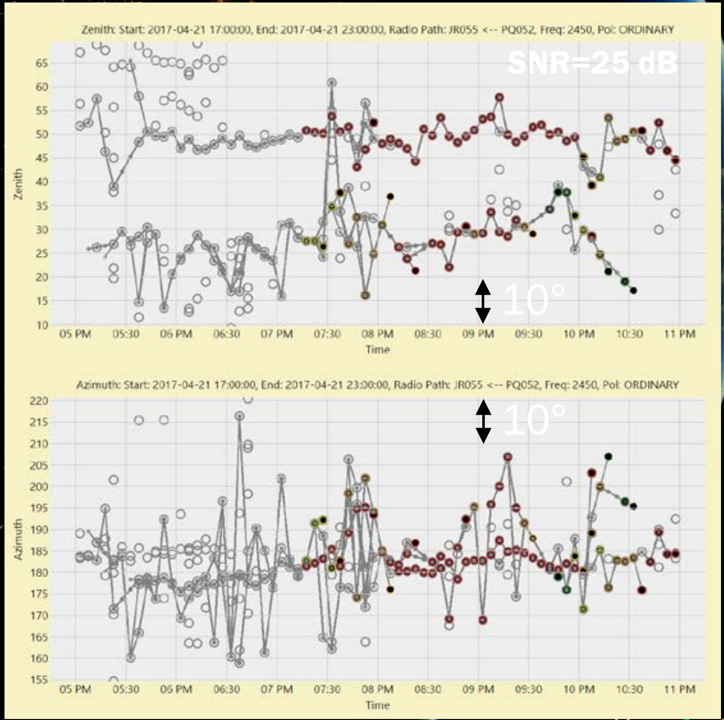
“EGU Opening” TID: 1700 to 2300 UT

Průhonice to Juiliusruh link (517 km) [“northern link”]

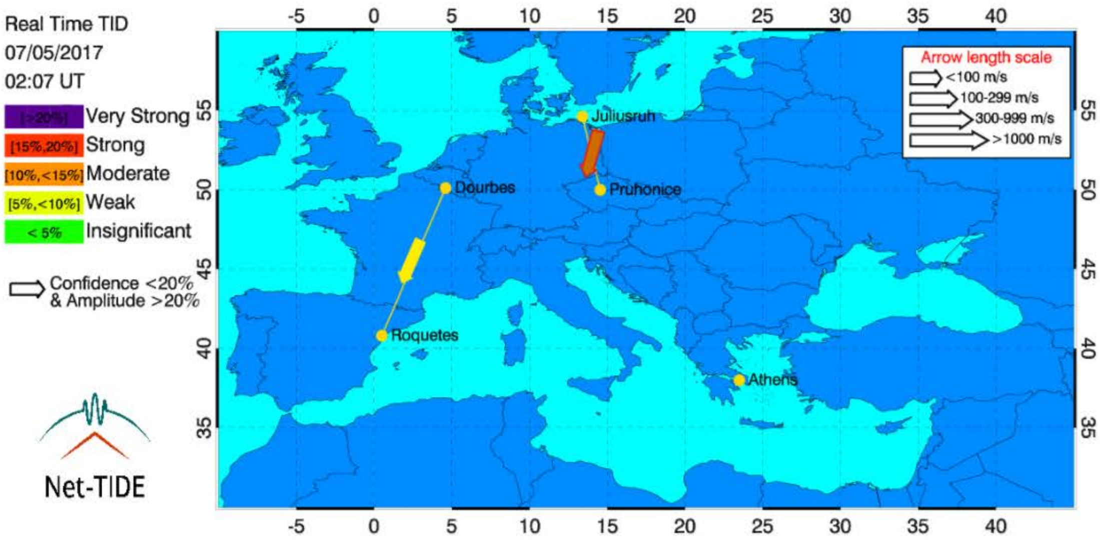




Net-TIDE warning system

TID Warning | About Net-TIDE | Rules of the Road | Help

Oblique | Vertical



Info

```
TID characteristics
Ref. Time: 2017-05-07T02:02:35.000Z
Ref. Loc(N,E,km): 14.0300 52.3000 221.000
Amp (%): 12.4000
Period (min): 130.000
Prop. Azim (CW): 196.100
Wavelength (km): 2000.00
Phase velocity (m/s): 256.410
Confidence (%): 0.00000
Uncertainty (%): 100.000

Link information
Tx/Rx: PQ052-->JR055
Distance (km): 517.000
Bearing (CW): 170.500
Ray Path (km): 736.000
OEL Cutoff (km): 627.000
An. win (min): 0.00000
```

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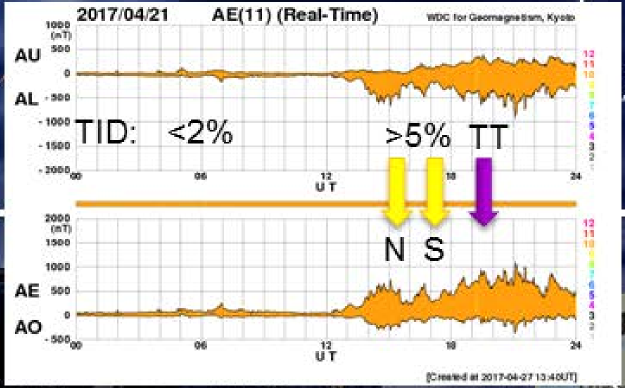
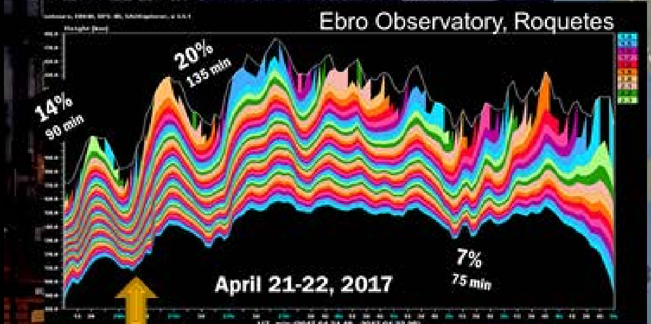
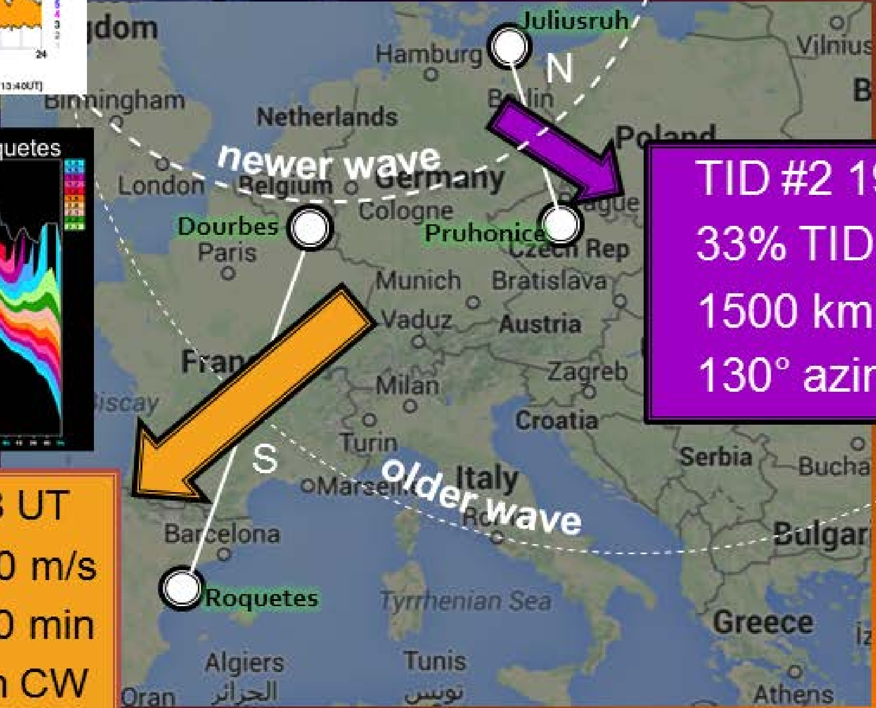


AE data courtesy WDC for GM, Kyoto





TID #2 19:47 UT
33% TID, 130 m/s
1500 km, 135 min
130° azimuth CW

TID #1 19:48 UT
15% TID, 410 m/s
2500 km, 100 min
245° azimuth CW

EGU 2017

Realistic Ionosphere = IRTAM + TID + RayRTIX

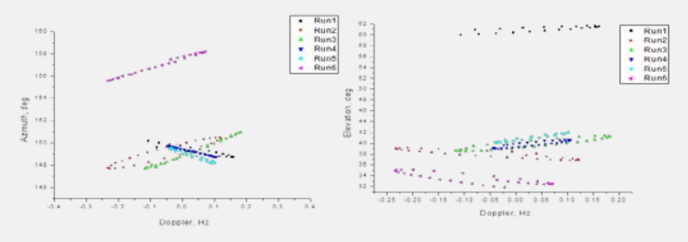
3. Ray Tracing through Realistic Ionosphere eXplorer

RayTRIX

Ray Tracing through Realistic Ionosphere Explorer

- RayTRIX is
  - HR2006 ray tracing code with Spitzer capability for NVI cases
  - Realistic Ionosphere: IRTAM+ TID + local tilt
- Currently offline, transition to GPU in progress

Prof. Xueqin Huang
1939-2016



Outlook

- Realistic Ionosphere combines IRI-based Real-Time Assimilative Model with TID Explorer detection of TID events for TID warning and HF raytracing applications
  - IRTAM is in operation since 2013
  - TID Explorer is scheduled for release in 2017
  - RayTRIX environment in early phase of testing
- IRTAM: close to completion; URSI INAG Working Group G.1 actively pursues real-time ionosonde network operation
- TID-X: RETID (USA) and Net-TIDE (Europe) projects support TID detection and evaluation using Digisonde oblique sounding data
- RayTRIX is in transfer to operations at LGDC

Acknowledgements: IARPA HFGeo, AFRL SBIR “RETID”, NATO SfP 984894