Realistic Ionosphere
with concepts for AI-driven ionosphere forecast

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Realistic Ionosphere, United Nations ISWI
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Global Ionosphere Radio Observatory
Lowell Digisonde International, LLC
GAMBIT Situation Room
Acknowledgements

- IGS Team (GNSS) of RION
  - Olsztyn UWM
    - Adam Froni
    - Andrzej Krankowski
    - Kacper Kotulak
    - Pawel Flisek
  - UTC/Barcelona
    - Manuel Hernández-Pajares
    - David Roma Dollase
    - Alberto Garcia-Rigo
  - AIRI/Beijing
    - Zishen Li
    - Ningbo Wang
- Metadata Definition Group
  - PITHIA-NRF Team
  - SPASE Consortium
    - Shing Fung
    - Leonard Garcia

- GIRO Science Team
  - Lowell GIRO Data Center
    - Bodo Reinisch
    - Xueqin Huang
    - Grigori Kmyrov
    - Sasha Kozlov
    - Artem Vesnin
  - ICTP/Trieste
    - Bruno Nava
  - INPE/São Paulo
    - Inez Batista
  - Boston College
    - Dima Paznukhov
- GIRO Engineering Support
  - Digsonde Crew
    - Ryan Hamel
    - 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
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

- 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

Opening by Prof. Bodo W. Reinisch
University of Massachusetts Lowell
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ADVANCES IN DIGISONDE DEVELOPMENT

67 Digisonde 4D units built since 2007
Ionogram in 1933 and nowadays

Credits to: Theodor Gilliland, NBS, USA
GIRO as of June 12, 2024
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 is not quite a Kalman filter
- Significantly 4DDA
- 24 hours of previous anomaly as observed at sensor sites
  - And then use diurnal harmonics of these anomalies

Suppose a GIRO ionosonde detects a significant 12-hour deviation $\Delta$. 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 BO

“Anomaly map” = Percent Deviation from Quiet Conditions
Free for academic use: GAMBIT Explorer UserApp 1.0A
Download from [https://giro.uml.edu/GAMBIT/](https://giro.uml.edu/GAMBIT/)

+ source code to integrate IRTAM coefficients from GAMBIT database with user applications
Anomaly maps by IGS and GIRO

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

ΔvTEC @ 6342 GNSS sites

ΔNmF2 @ 60 GIRO sites

vTEC data courtesy MIT Haystack Madrigal Repository

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

Slab Thickness: weather-minus-climate

VTEC: $10^{16}/m^2$

NmF2: $10^6/cm^3$

2021-11-04 23:15 UT
2. RayTRIX CQP

~5 sec running time

OBLIQUE TRACE SYNTHESIZER

Choose station pair or type coordinates below.

Station Pair: PO052 to /R055

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

MUF
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 Inez Batista, INPE
Sausages in the Sky?

Jicamarca skymaps courtesy of Oscar Alfredo Veliz Castillo, JRO
4. TID Detection

Ebro Observatory, Roquetes

April 21-22, 2017

40% 90 min

70% 135 min

hmF2

1.4 MHz

20% 75 min
HF versus other TID sensors

- **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

Data courtesy Tobias Verhulst, RMI
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

Ebre
Dourbes
Juliusruh
Tromso
Sodankyla
St. Petersburg
Průhonice
Sopron
Belgrade
Rome
Dourbes
El Arenosillo
Lampedusa
Nicosia
Athens
Kaliningrad
Warsaw
Tromso

1062 km
1150 km
920 km
5712 km
228 km
923 km
Forecasting Ionosphere

Using Natural Language Processing (NLP) approach
“Triggered” storm option in IRI

Forecast by analogy to an average “anomaly” storyline

reminded “average” storm behavior
(adjust 1024 expansion coefficients)
Next: Library of the storm storylines
instead of the “average storm timeline”

- Instead of an “average” storm, keep a library of previous storylines of $\Delta NmF2$ 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 $\Delta NmF2$ 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

- learned next step of the ionospheric dynamics
- and keep going forward

CONTEXT WINDOW

Location/DOY/etc.

ionospheric drivers and previous state
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) network topologies
  - Support interpretation of subelements in the context of other cues
  - 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

- Forecast by analogy
- Retrieved best match among stored anomaly storylines
  - Adjust expansion coefficients
- Time to impact (variable)
- Timing is also variable
- Quiet-time behavior
- Storm onset time
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 $\Delta NmF2$ to correct for actual-vs-library timing
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
Both positive and negative anomalies present at the same time.

Total 1024 coefficients.

To produce the 1-day weather forecast, the retrieved historic storm timeline is referenced to the ongoing storm onset, magnetized, and superimposed on the relevant quiet time reference.

Can be expanded to 2 or 3 days.
Memory of 48-hour 2048-coef timelines

48-hour Climate map (IRI)

48-hour Weather map

Forecasting with Dynamic Time Warping

Storm onset time

Dynamic Time Warping

Unwarping

re-magnetize
Memory of 24-hour 1024 coef timelines
re-magnetize

24-hour Climate map (IRI)

24-hour Weather map

Storm onset time

Best match

Driver storylines

Forecasting by context-driven memory
Forecasting by context-driven memory (2)
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

Capturing Context of Ionospheric Dynamics
Natural Language Processing as DTW example

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