COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 September – 10 October 2025
Trieste, Italy

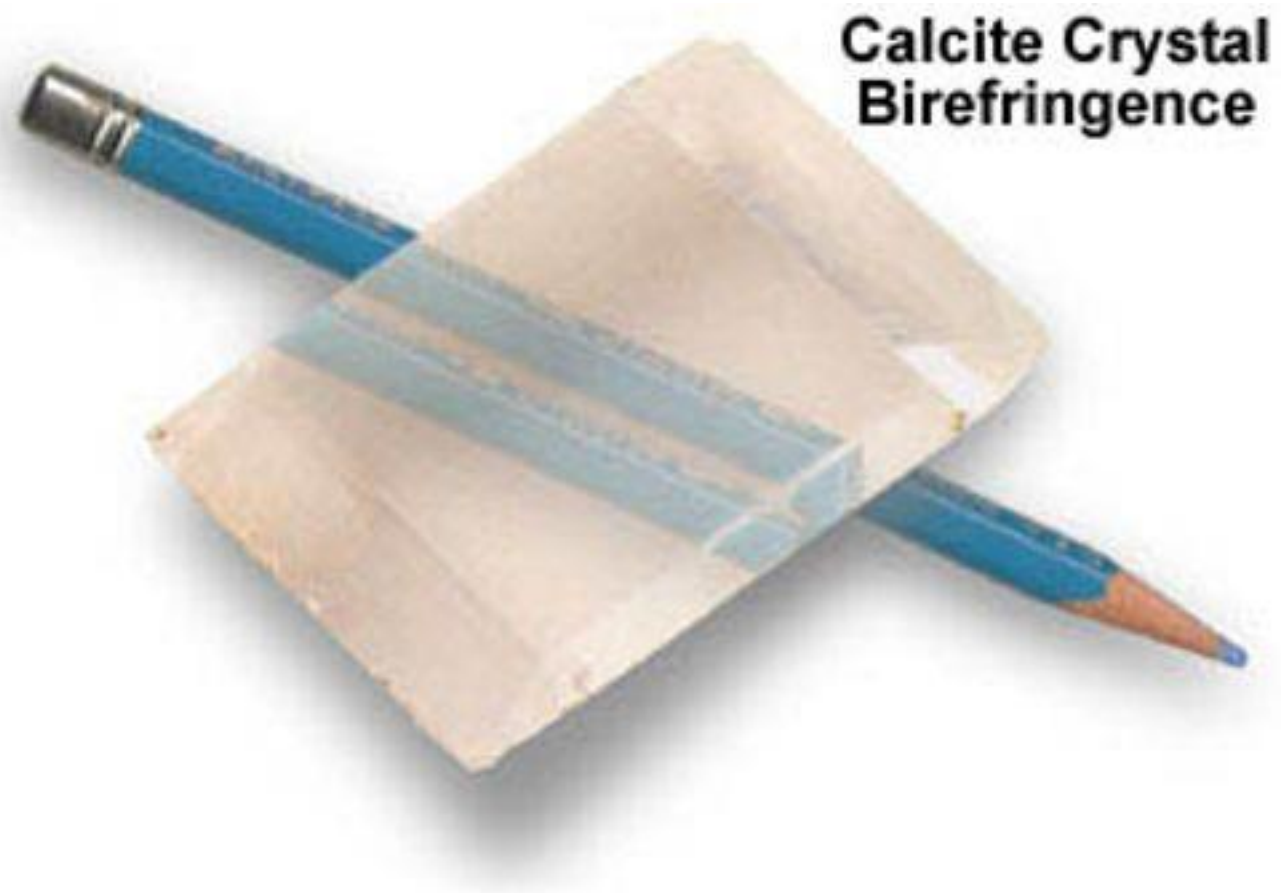
IONOSONDES

and the measurements they take

Presented by Ivan Galkin
University of Massachusetts Lowell, USA

IRI Capacity Building Workshop 2025
Trieste, Italy • 30 September 2025

Prelude I



Prelude 2: Columbus' Discovery

- **Much like a Scientific Discovery**
  - Grand idea: the Earth is round and, by sailing West, my ship can reach India
    - Not an original idea, but he got new information
    - Terrible ordeal looking for funding
    - Did not find India, found something else
    - In spite of all evidence, remained convinced he found India
    - No recognition of his accomplishment during his lifetime
    - Multiple proofs he was not the first European to reach America

Marconi's Discovery

- **Somewhat resembling Columbus'**
- **Grand-idea: radio can be used for over-the-horizon communications**
  - Not a terribly new idea, but new application for the long-distance comms
    - Everyone believed the radio wave are good for line-of-sight propagation
      - Henrich Herz radio wave demo in 1888,
      - Oliver Lodge Rx/Tx spark gap telegraph in 1894
  - Breakthroughs: First Transatlantic radio link between Canada and UK in 1901
  - Multiple evidence that someone else did similar things before
    - Alexander Popov report in 1896 on 14 km link from coast to ships
      - Popov's results did not reach public due to their Top-Secret classification
      - Popov did not think much of his results and changed his interests

Historical Reference: High Frequency

skywave

The world goes wireless, most extraordinarily

Ionosonde Weather Service

The world goes into space, most extraordinarily

1901 — 1920 — 1925 — 1930s — IGY (150 ionosondes) — ISR era — 1990 — RO era

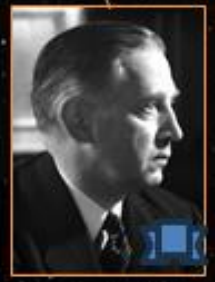
1922 — WW2 (radar era) — 1956-1957 — GPS era (with tomography) — TID era

1970s peak of interest in ionospheric radio

HF Dead declarations

First ionosondes!

Marconi



Appleton

22 SEPTEMBER PRE-FORUM SCIENCE DAY
23-26 SEPTEMBER XVI INTERNATIONAL GIRO FORUM
IGF 2025

COSPAR
COMMITTEE ON SPACE RESEARCH

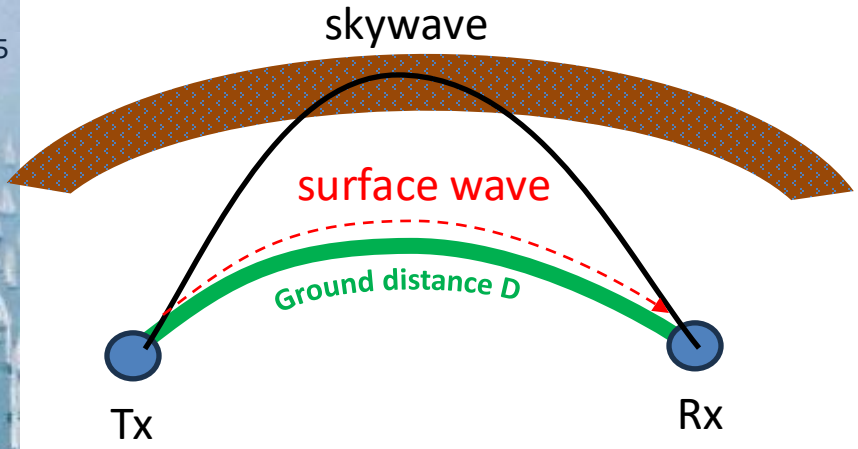
IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

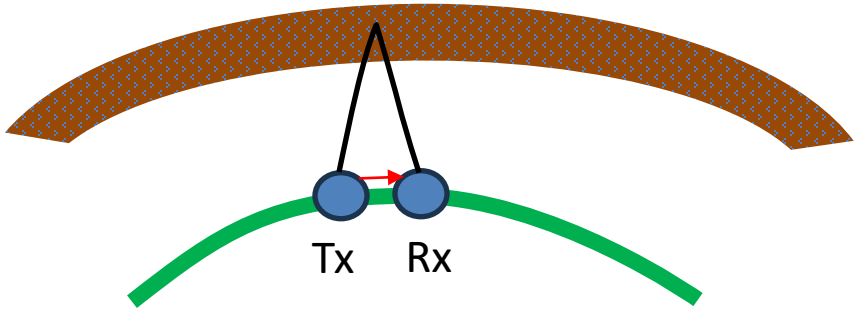
Celebrate!

Happy 100th Anniversary of the Ionosonde Invention!

- **In the 1920s, the ionosphere was the most fashionable object to study in geophysics**
  - A conducting layer in the atmosphere © 1902
    - a.k.a. "Magical Mirror in the Sky"
      - responsible for Marconi's skywave in 1901
    - BBC started radio broadcasts in 1922
- **The Quest: How high in the atmosphere is that mirror?**
  - 1925: Two groups reported success!
    - Appleton and Barnett at the Cavendish Laboratory in Cambridge
    - Breit and Tuve at Carnegie Institution of Washington

Skywave Existence Proof, 1925





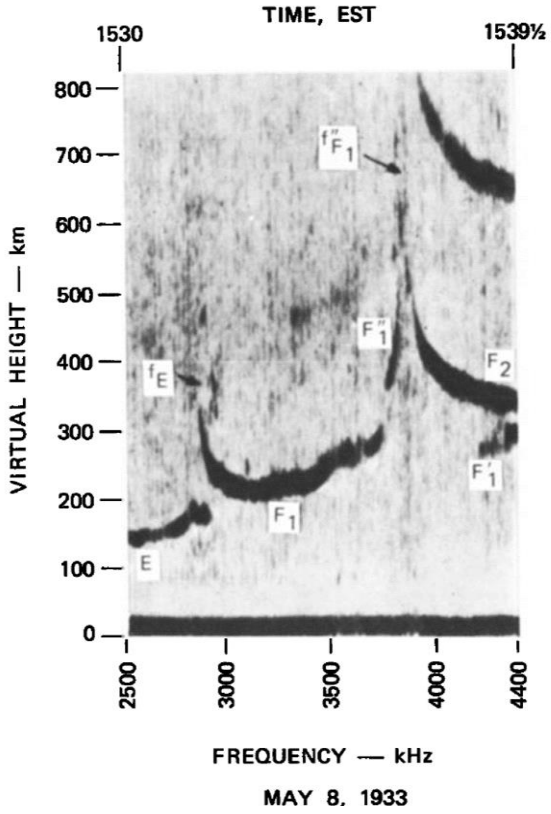
- **Sir Appleton Experiment**
- **Used BBC transmitter**
  - Continuous Wave (CW)
  - Frequency control
- **Made frequency changing during transmissions**
  - Frequency modulation
- **Received signal is a mix of the surface and sky waves**
  - But phases are different so these waves interfere
  - Amplitude recorder was enough
- **FMCW sounder was built first, pulsed (radar) second**

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

The 1930s Challenge

- **Radio broadcasters in the 1930s: make ionosonde a weather service**
  - (for HF frequency management)
- **Challenge: transform ionosondes into *automatic* machines**
  - 1931: six people to run one ionosonde
    - Regular observations were not a small feat!
    - No wonder **11 Jan 1931** is the celebrated mark in out community
      - Slough observatory produced the first diurnal timeline of foE



Theodore Gilliland's group at NBS (USA), 1933

Historical Reference: High Frequency

skywave

The world goes wireless, most extraordinarily

Ionosonde Weather Service

The world goes into space, most extraordinarily

1901 — 1920 — 1925 — 1930s — WW2 radar era — 1956-1957 — ISR era — 1990 — RO era — TID era

1922

IGY
150 ionosondes

GPS era
with tomography

1970s
peak of interest in ionospheric radio

HF Dead
declarations

Marconi

Appleton

First ionosondes!

22 SEPTEMBER PRE-FORUM SCIENCE DAY
23-26 SEPTEMBER XVI INTERNATIONAL GIRO FORUM
IGF 2025

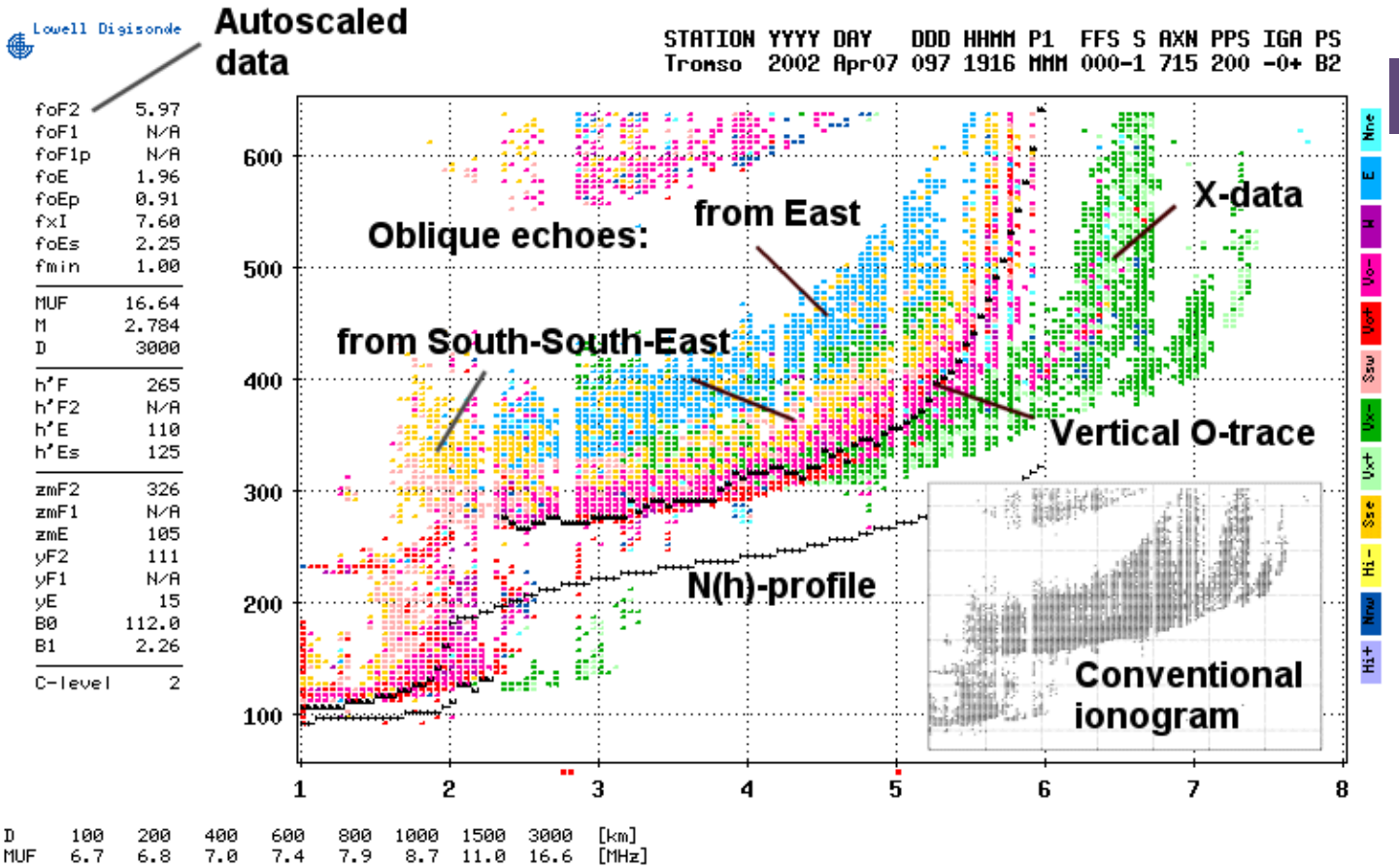
IRI: used ionosondes to model foF2

- **During the IGY 1956-1957, ~150 ionosondes were collecting ionograms continuously**
  - Was there any other sensor data?
- **Acquired data used to build global climatology maps of foF2 and M(3000)**
  - Jones and Gallett work in the 1960s
    - Used custom spatial expansion basis with 76 terms
    - Even though spherical harmonics math was readily available, custom basis design was introduced
      - Optimal for representation of the Appleton anomalies
      - Used modip angle (credits to Rawer) to represent dependence of foF2 on the [changing] magnetic field of the Earth
      - Had a special factor to suppress anomalous shootout at the poles
- **Additional work: hmF2 for IRI**
  - Derived from foF2 and M(3000)
  - Used until Shubin model became available (radio occultation measurements)

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Fast forward to the 1970s



Digisonde ionogram data courtesy: The Arctic University of Norway

ARTIST Family

- APE (1974)
- BISA (1981)
- ARTIST (1982)
- ARTIST-II (1986)
- ARTIST-III (1991)
- SARTIST (1991)
- ARTIST-B (1994)
- ARTIST-4 (1996)
- ARTIST-4.5 (2004)
- ARTIST-5 (2002)
- ARTIST-6?

Historical Reference: High Frequency

skywave

The world goes wireless, most extraordinarily

Ionosonde Weather Service

The world goes into space, most extraordinarily

1901 — 1920 — 1925 — 1930s — WW2 radar era — 1956-1957 — ISR era — 1990 — RO era — TID era

1922

IGY
150 ionosondes

GPS era
with tomography

1970s
peak of interest in ionospheric radio

HF Dead
declarations

Marconi

Appleton

First ionosondes!

22 SEPTEMBER PRE-FORUM SCIENCE DAY
23-26 SEPTEMBER XVI INTERNATIONAL GIRO FORUM
IGF 2025


UMASS LOWELL
GIRO
Real-time sites
Retrospective only
In progress
Nord
Qaanaaq
Thule
Poker Flat
Eielson
Gakona
King Salmon
Eareckson
Idaho National Lab
Boulder
Albuquerque
Dyess
Pt. Arguello
Austin
Kent Is.
Eglin
Melrose
Alpena
Millstone Hill
Wallops Is.
Bermuda
Ramey
Lualualei
Sondrestrom
Narsarsuaq
Goose Bay
Tromso
Kalinigrad
St. Petersburg
Moscow
Warsaw
Rostov
Sopron
Julius ruh
Fairford
Chilton
Pruhonice
Dourbes
Rome
Roquetes
Lajes
El Arenosillo
Gibilmanna
San Vito
Athens
Nicosia
AlDhafra
Al Dhafra
Ilorin
Norilsk
Salekhard
Novosibirsk
Irkutsk
P.Tunguska
Zhigansk
Yakutsk
Magadan
Petropavlovsk
Khabarovsk
Mohe
Anyang
I-Cheon
Beijing
Almaty
Jeju
Misawa
Awasi
Wuhan
Shaoyang
Sanya
Chung-Li
Delhi
Hainan
Ahmedabad
Gadanki
Trivandrum
Guam
Wake Is
Kwajalein
Belem
Boa Vista
Sao Luis
Fortaleza
Cachimbo
Jicamarca
Campo Grande
Cachoeira
Paulista
Tucuman
Santa Maria
Ascension Is.
Louisvale
Madimbo
Grahamstown
Hermanus
Niue
Cocois Is.
Darwin
Townsville
Brisbane
Norfolk
Learmonth
Perth
Camden
Canberra
Bundoora
Hobart
Port Stanley
TBD
Troll
Zhong Shan
Casey
Jang Bogo

IDAR

IONOSONDE DATA ACQUISITION FOR RESCUE

Ivan Galkin

UMass Lowell Space Science Laboratory

22 SEPTEMBER PRE-FORUM SCIENCE DAY

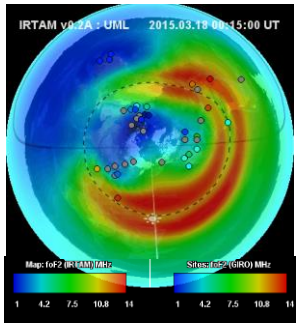
IGF 2025

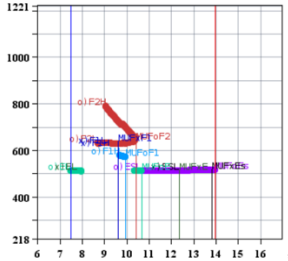
23-26 SEPTEMBER XVI INTERNATIONAL GIRO FORUM

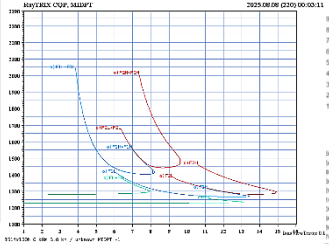
COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

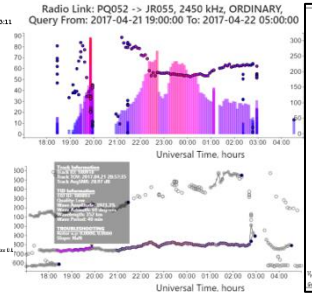
Main Ionosonde Real-Time Products

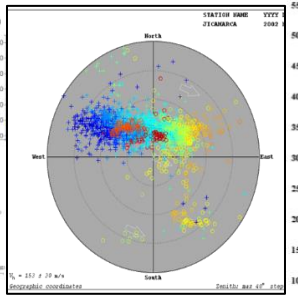


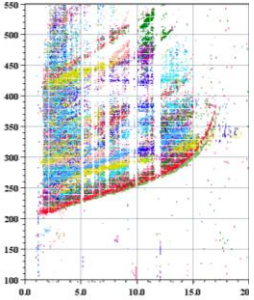




Dourbes to Athens







GIRO
including DIDBase

GAMBIT
including IRTAM 3D

LOIA
including LOUIBase

RayTRIX

TID Explorer

SkyLITE

IDI

1. Measurements

2. Global Weather Modeling

3. Oblique Ionograms

4. HF Signal Raytracing

5. TID Warnings

6. Plasma Drifts

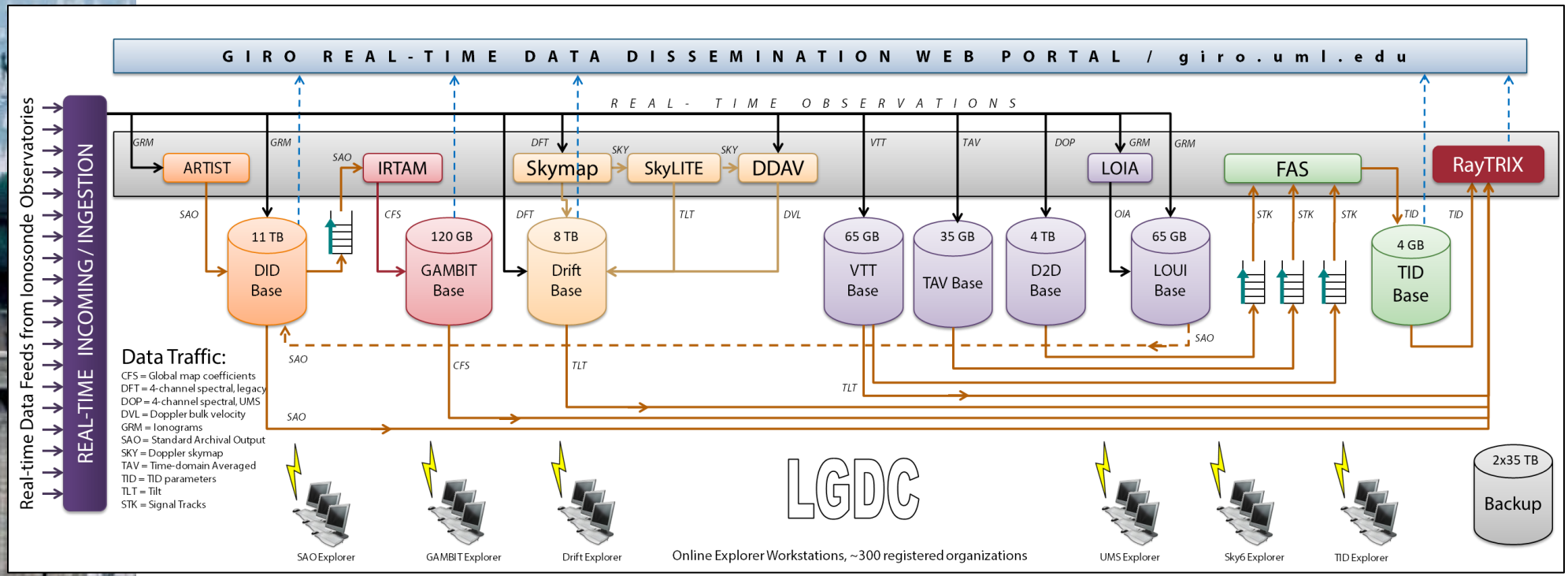
7. Disturbance Indicator

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

LGDC Products and Services

FOR SPACE WEATHER MONITORING



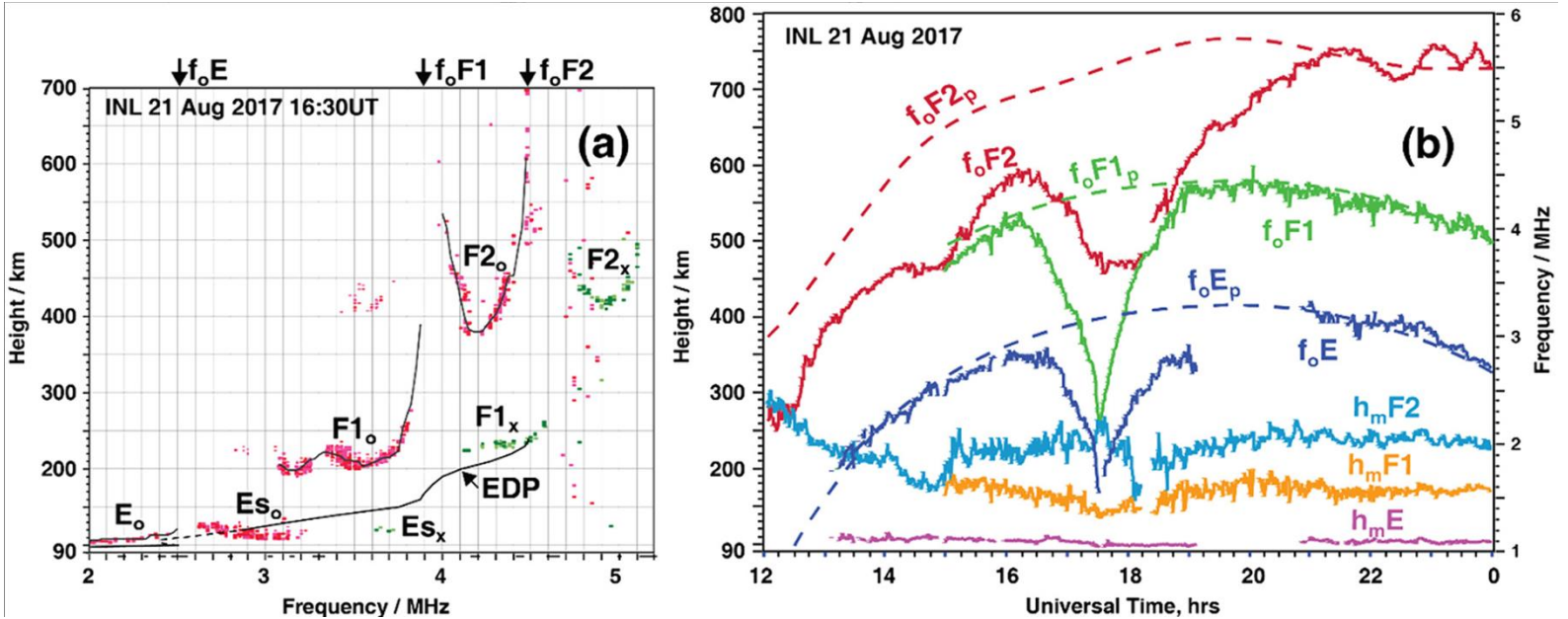
COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct ‘25
Trieste, Italy

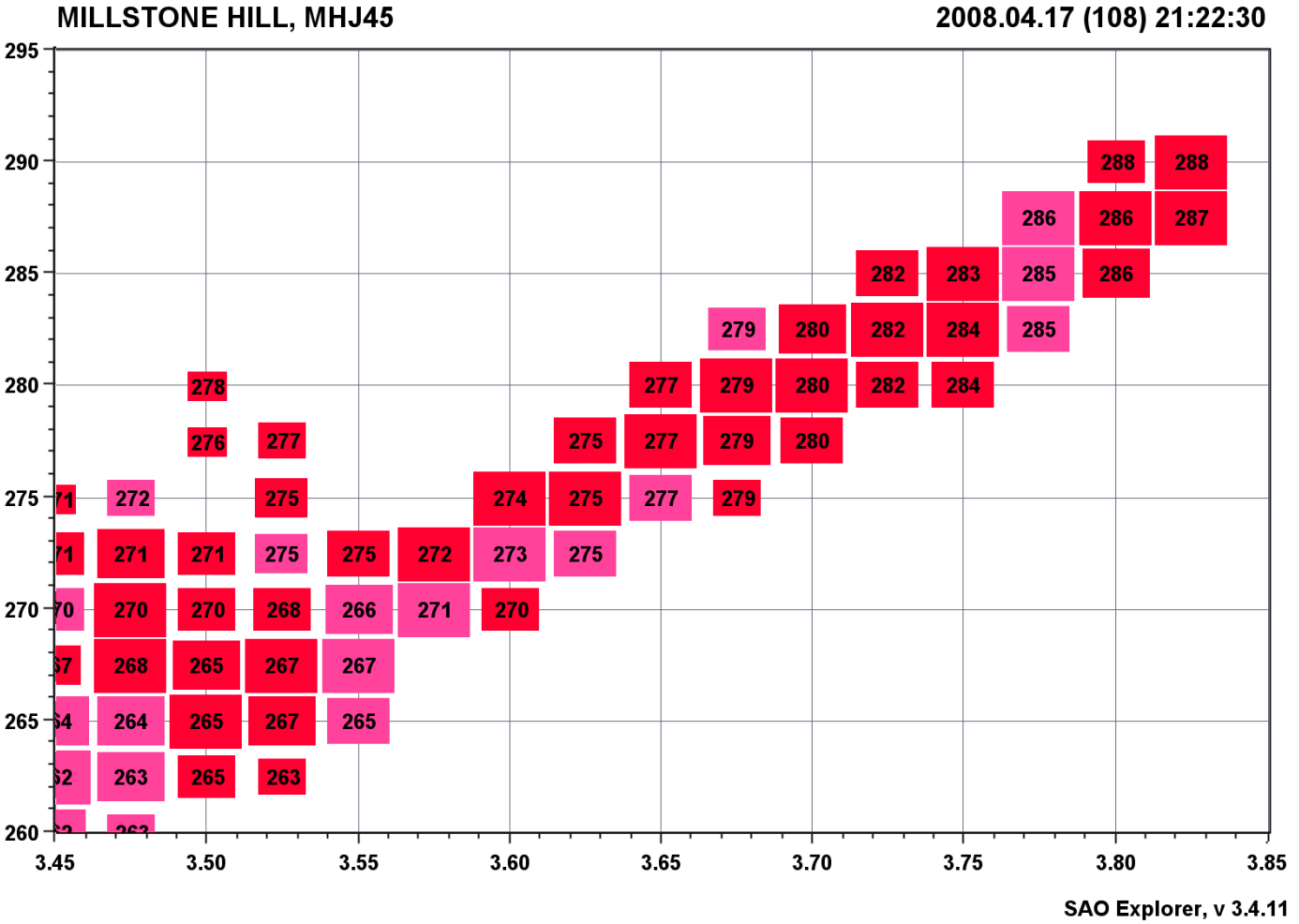
Why Ionosondes?

Ionosonde: GROUND TRUTH

- **Good reference-quality data going back to the 1940s**
  - 800 publications per year with ionosonde contributions



Precision Ranging of Digisonde

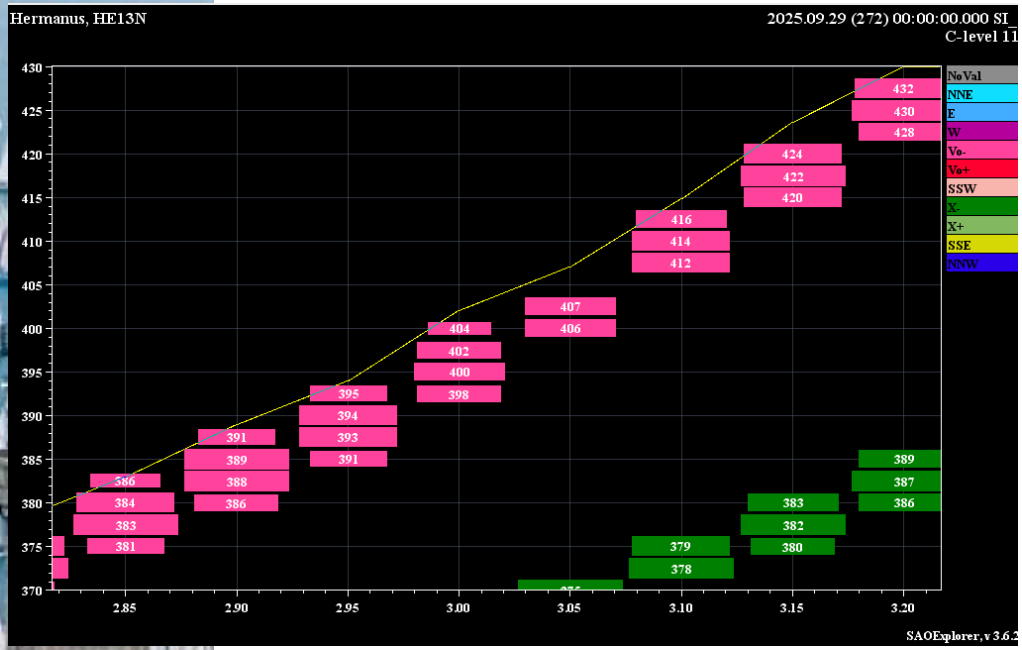


COSPAR
COMMITTEE ON SPACE RESEARCH

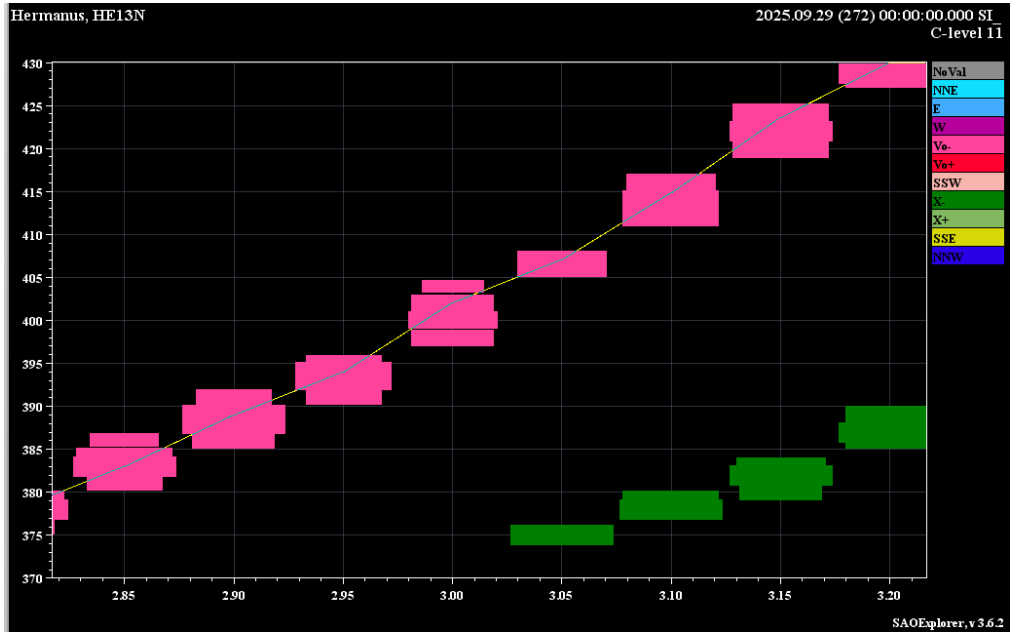
IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Precision Ranging in Digisonde

Hermanus Digisonde data courtesy John Bosco Habarulema, SANSA



Precision range is available for each bin



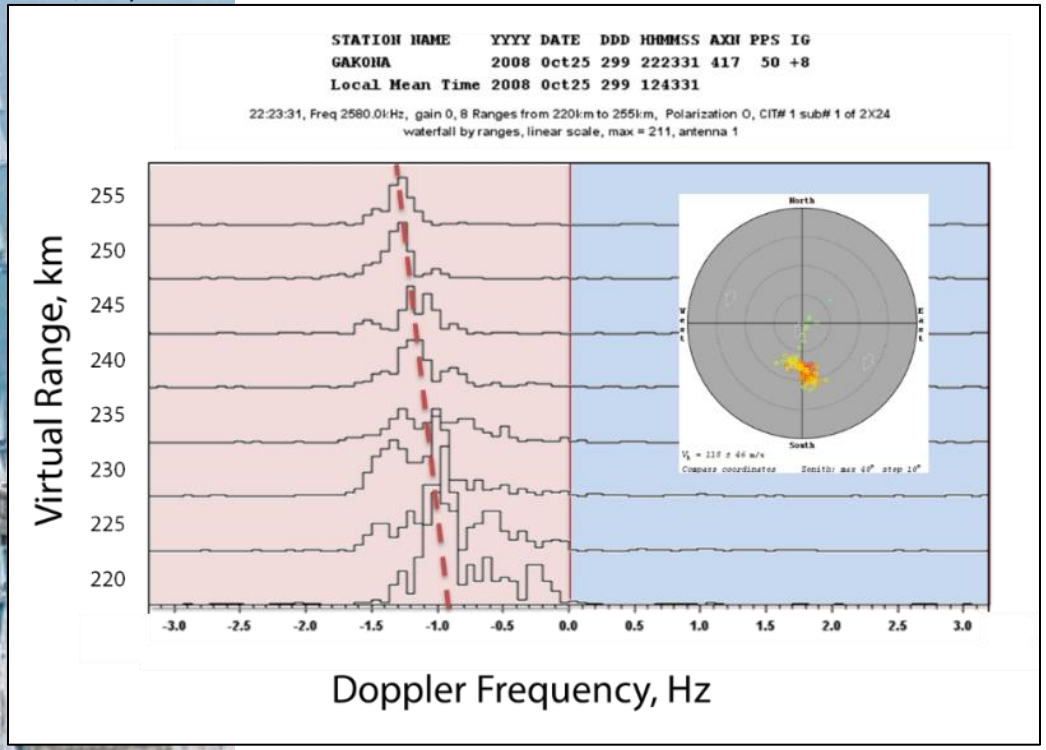
After precision range is applied

Automatic correction of zero range bias; sub-pixel accuracy of ranging is 1 km

Ionosonde path forward: Why?

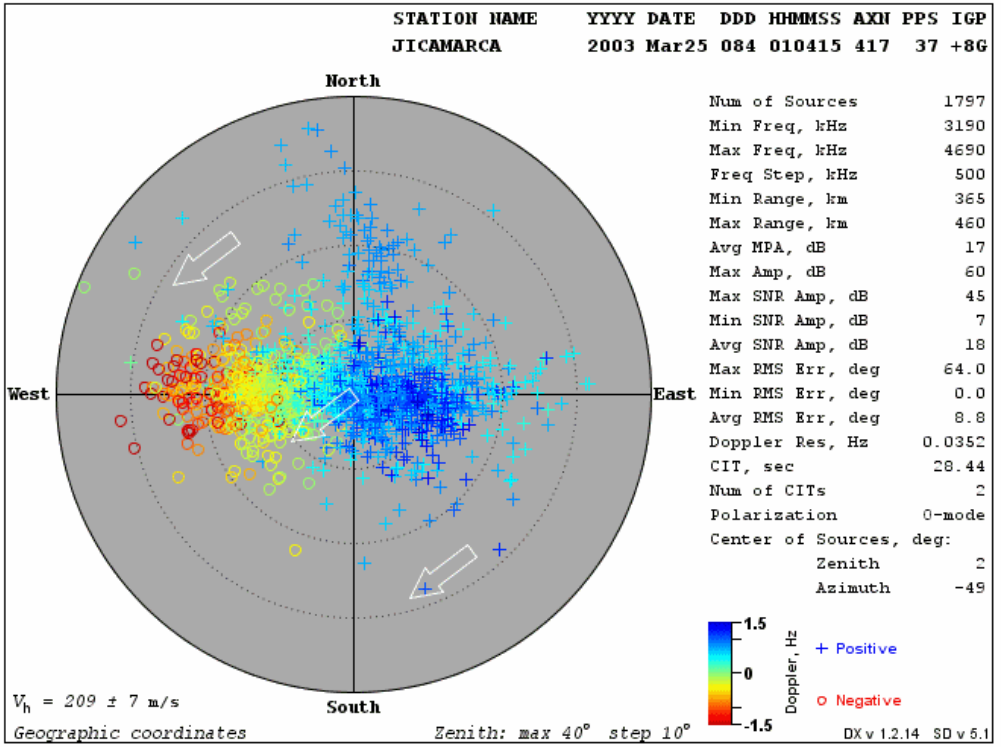
IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Digisonde skymap data courtesy: AFRL Gakona



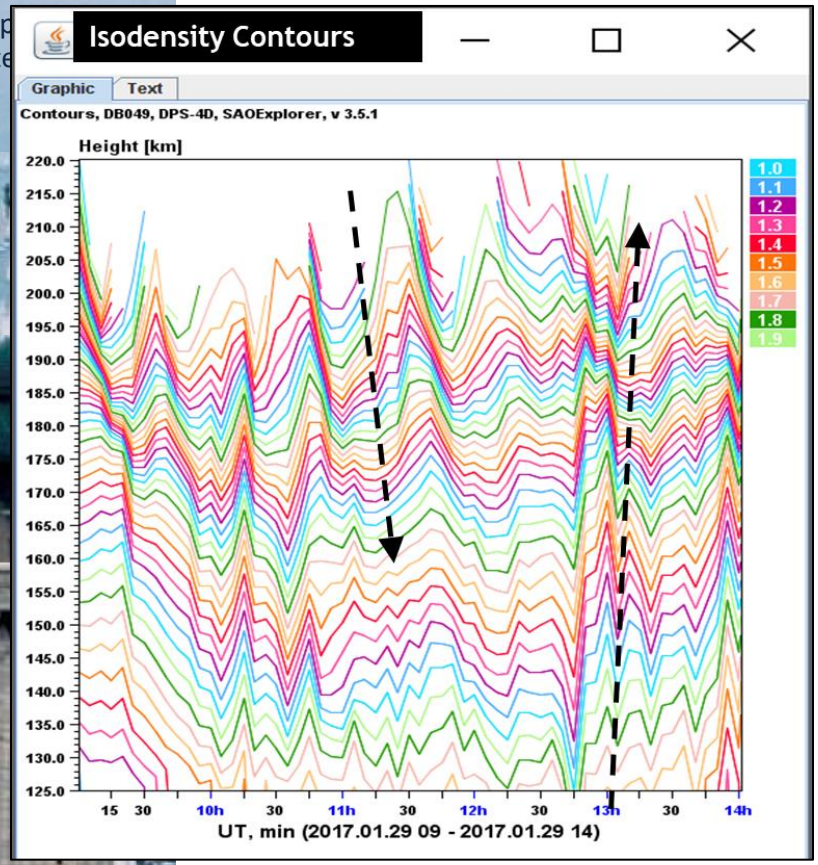
Plasma acceleration above the HAARP-heated area

Digisonde skymap data courtesy: JRO



Digisonde's view of the equatorial bubble passages

Path forward: Why?



HIGH SENSITIVITY TO PLASMA IRREGULARITIES:

- **Sensitivity to TIDs**
  - Detection of a 5% TID vs underlying density
    - What GNSS sees as 0.05 TECU modulation, the ionosonde sees as 50% local disturbance
    - This is because the ionosonde's probing signal "pin-points" a specific altitude in the ionosphere
  - Ionosonde: "TID are always present" < 2%
- **1D Altitude profile of TID (pin-pointing capability)**
  - Detailed view of propagation along z-axis
- **Direction, Velocity, Wavelength of TID with two ionosondes**
- **Direct measurement**
  - Ionosonde is a static platform (no spacecraft motion effects)
  - Relatively few assumptions are made about the ionosphere
- **24/7 operations with automatic intelligent system analysis**
  - Replicated human intelligence

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct ‘25
Trieste, Italy

Ionosondes: who cares?

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Path forward: Who Cares?

- Space Weather applications
  - Ionosonde: global data within minutes
    - Oblique sounding over no-ionosonde areas!
      - e.g., South Korea to Japan link to monitor TID activity for the undersea earthquake/tsunami detection
  - A suite of assimilative models with ionosonde input (more about it today!)
    - including HF signal propagation models
    - Provide boundary conditions for MI coupling models
- Instrument Collaborations
  - Data fusion projects
  - Reference-quality data for various CalVal campaigns
- Scientific applications
  - Untapped information
    - Lesser-known ionosonde operational modes

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Who cares: global prompt data

Global Ionosonde Observation/Operation Network (GION)

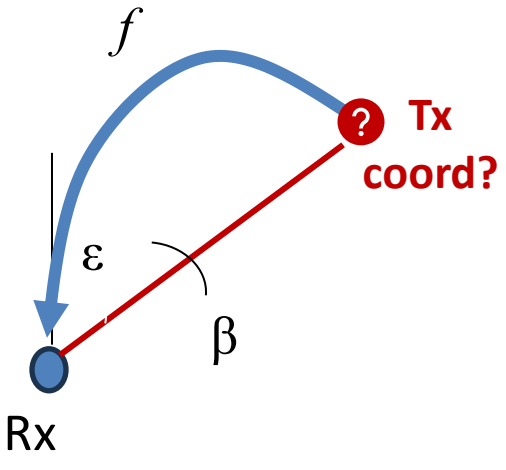
- Multi-agency advisory committee
- Established in 2025
  - UNOOSA for international cooperation in outer space
- Objective: combine all ionosonde networks into an ionospheric weather monitoring consortium
- Lowell GIRO Data Center (LGDC) funded to support GION
  - Historical and real-time ionosonde data management
  - SAO V6 standard for ionosonde data exchange

COSPAR
COMMITTEE ON SPACE RESEARCH

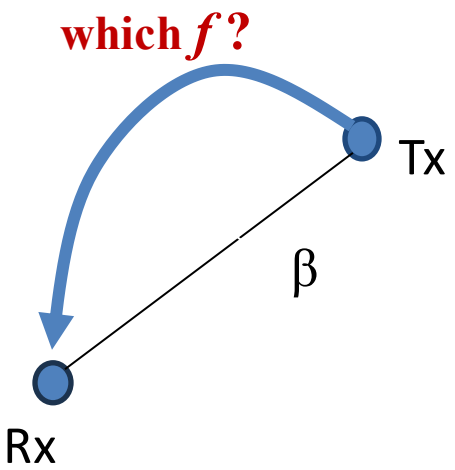
IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Who cares?

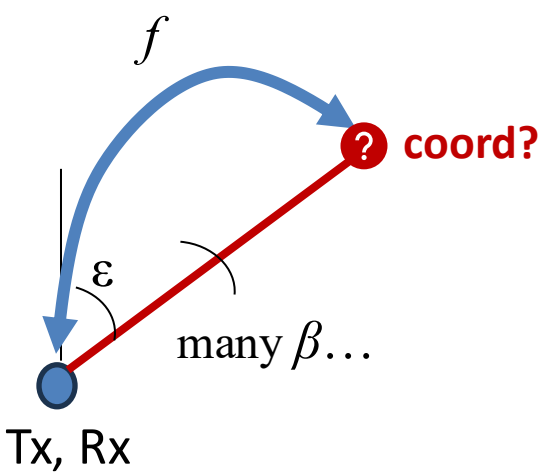
Three scenarios of HF signal modeling



GEOLOCATION
of uncooperative transmitters



FREQUENCY MANAGEMENT
of HF communications



OVER THE HORIZON RADAR
searching reflecting targets
also in backscatter mode

POLIZEI HFGEO

PECASUS FOR ICAO HAM RADIO

ONERA
THE FRENCH AEROSPACE LAB

Who cares: Data fusion

- GNSS+GIRO
  - VTEC+NmF2
    - Fusing GIMs with IRI and IRTAM
  - GPSII model
  - Ionosonde-assisted Tomography
  - Radio Occultation + GIRO
    - Model-constrained assimilation of 24-hour measurements
  - Assimilative IRI
    - projecting VTEC anomaly to NmF2 anomaly

Who cares: Calibration/Validation

- The original CalVal: Naval Research Lab's project of UV sensors
  - F17 (2004-2008) and F18 (2010-2011) Spacecraft
  - DIDBase was built in 2004 to support this CalVal
- COSMIC validation (2006)
- New developments:
  - GNSS bias elimination with GIRO ionosonde inputs
  - DISPEC project: coincidence analysis with Swarm/GRACE

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Who cares: Academia

- Hot topics in academic/applied research
  - D-region specification with Digisondes
  - Sporadic E layer
  - Earthquake (detection and precursor investigations)
  - Equatorial plasma bubbles
  - Auroral research (in support of the Arctic exploration)

Efforts to build Real-Time IRI

- **Original concept dates back to 2009**
  - Task Force on Real-Time IRI
- **Real-time IRI is a subset of a wider Assimilative IRI**
- **Assimilative IRI: smoothly transformed IRI definitions to match available measurements**
  - Effective Sunspot Number IG (1970s)
- **Real-Time Assimilative IRI: use low-latency measurements**
  - Ionosondes
  - GNSS…

IRTAM

- **IRI-based Real-Time Assimilative Model**
- **Every 15 minutes releases new coefficients**
  - foF2, hmF2, B0, and B1
- **The IRTAM coefficients can be freely downloaded**
  - https://giro.uml.edu for the landing page (humans)
    - https://lgdc.uml.edu/rix/gambit-coeffs?charName=CC&time=TT
      - CC is foF2, hmF2, B0, or B1
      - TT is ISO timestamp YYYY.MM.DD'T'HH:MM
        - » Coverage: 2000 to current
  - Academic use only, the latest 4 hours are restricted
- **The IRTAM coefficients are given to IRI-2020 to replace quiet-time coefficients**
  - "Climate" IRI becomes "Weather" IRI
  - pyIRTAM is available from NRL, uses IRTAM coefficients

COSPAR
COMMITTEE ON SPACE RESEARCH

IRI CCBW 2025
29 Sep – 10 Oct '25
Trieste, Italy

Example IRTAM download

```
# START_HEADER
# GLOBAL IONOSPHERE RADIO OBSERVATORY (G.I.R.O.)
# giro.uml.edu
#
# IRI-based Real-Time Assimilative Model (IRTAM)
#
# IRTAM Coefficients of Temporal-Spatial Expansion
# Generated by GambitCoefficients_Servlet GX.Global.Svlt 0.3b on 2025-09-29T09:49:42.456Z
# Ionospheric Characteristic: foF2 [MHz]
# Time of Validity 2021-05-05T10:00:00.000Z
# Assimilative Engine: NECTAR v0.2A
# Earth Grid: 46 lats x 45 lons
# Expansion Basis: JonesGallet_LinTrend
# Basis Lengths: 14(temporal) x 76(spatial)
# Assimilated stations:
# AL945 AS00Q AT138 BC840 BR52P BVJ03 CB53N DB049 DW41K EA036
# EA653 EB040 EG931 EI764 FF051 FZA0M GA762 GM037 GR13L GU513
# HE13N HO54K IF843 JB57N JR055 KB547 KL154 LL721 LM42B MA155
# MA560 MHJ45 MO156 MZ152 ND61R NI135 NI63_ NV355 PA836 PE43K
# PF765 PK553 PQ052 PRJ18 RV149 SAA0K SH266 SMK29 SO148 THJ76
# TR169 TR170 TV51R TZ362 VT139 WA619 WP937
# Requested by unknown from IP:10.157.147.21
# END_HEADER
  5.87953870e+00 -1.44939298e-01  1.25655436e-01 -2.42336456e-01
 -1.75973637e-01  1.54009262e-01 -1.39515268e-02 -1.19648304e-02
 -9.39705867e-02 -1.95793009e-02  5.57981271e-03  2.73829158e-02
 -2.95881461e-03 -1.50430237e+00  3.55188053e-01  3.32249181e-01
  6.67634727e-02 -3.94956554e-01 -9.92984803e-03 -2.14465534e-01
  3.65567284e-02 -2.16518322e-02  4.43464706e-02  1.35534191e-01
  1.54566996e-01  6.49715902e-02  1.26694202e+01  3.58279106e+00
  2.15255600e-01  1.62224261e+00 -7.22932143e-01 -3.38449181e-01
  3.19914819e-01  1.95202336e-01  2.12027550e-02 -1.05328821e-01
  1.13302375e-01 -3.94735259e-01 -2.54224937e-01  1.61858852e+01
 -6.22430209e+00  3.15664771e+00 -2.87885914e+00  3.46736197e+00
 -1.81862775e+00  1.05099400e-01  2.12410716e-01  3.45073958e-01
  1.62686811e-01 -2.78810570e-01 -1.12016392e+00 -7.49714200e-01
 -8.27104427e+01 -2.49222095e+01  9.45798245e-01 -9.95035349e+00
  2.78172067e+00  5.56545791e+00  7.40654876e-01 -3.74370508e-01
  2.05937317e+00  1.16587697e+00 -1.04607422e+00  1.55344768e+00
  2.30311580e+00 -2.16634168e+01  3.25514419e+01 -2.16535025e+01
  8.25515183e+00 -1.10288210e+01  1.46159451e+01  3.33768063e+00
 -3.03053374e+00  1.92837099e+00 -1.33115558e-01  1.22634601e+00
```