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UNIVERSITY OF NEW BRUNSWICK

Canadian
High
Arctic
Ionospheric
Network

Results of using low-cost instruments for Space Weather research (including GNSS and HF-radars)

A. Kashcheyev

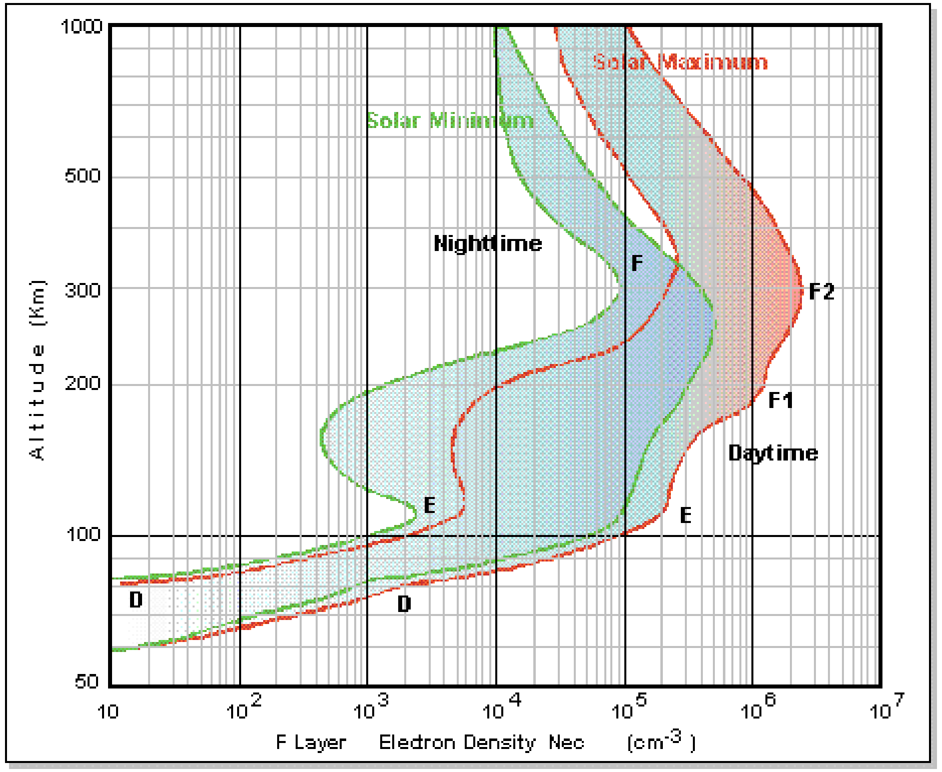
epartment, University of New Brunswick, Fredericton, Canada

The Abdus Salam
International Centre
for Theoretical Physics

Outline

- Intro
- Motivation
- History
- SDR HF receivers/radars
- Dual frequency GNSS
- Conclusions

Ionosphere



- Ionized part of the atmosphere from ~60 to few thousand km above the ground, so-called magnetized cold plasma or weakly ionized gas
- Formed by solar radiation, namely by photochemical absorption processes
- Loss is due to recombination processes
- Due to different ionization production and loss processes the electron density profile with altitude shows a layered structure that changes with time, location and solar activity
- The borders between layers are inflection points in the ED profile
- It is accepted to distinguish D, E and F (F1 and F2) layers
- Structure is highly dynamic and depends on many parameters

Ionosphere effects on radio signals

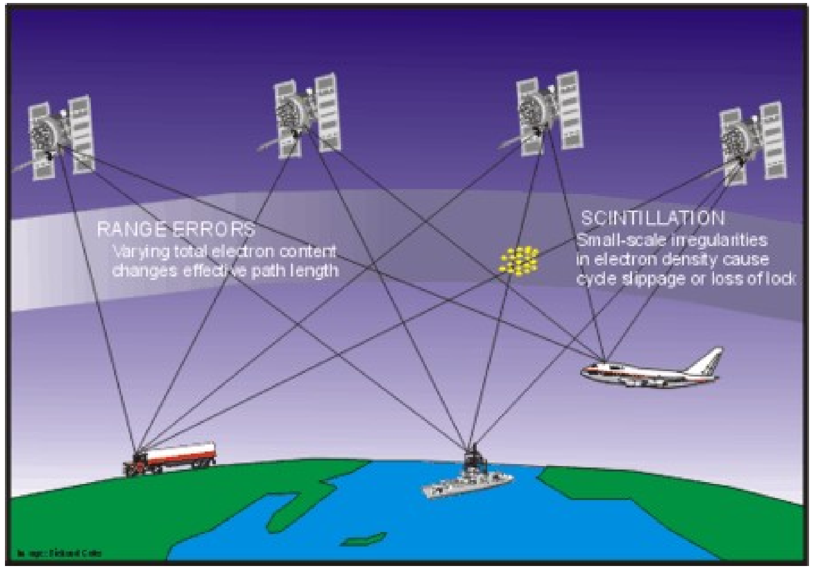


Image: Richard Cole

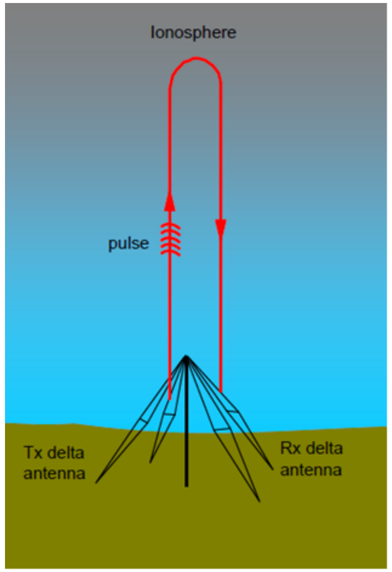
- **Range errors**
  - Group delay
  - Phase advance
  - Depend on the electron density along the ray path

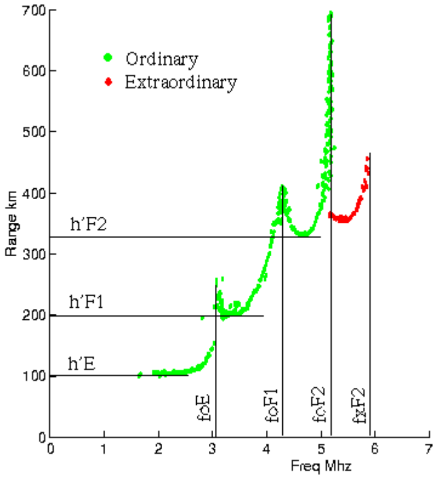
$$d = \frac{40.3}{f^2} \int_{sat}^{rec} n_e \, dl$$

  - Highly variable with time/space
- **Scintillation**
  - Rapid random changes in amplitude and/or phase of the signal
- **Doppler shift**
  - Change in carrier frequency

Most common ionospheric instruments

Ionosondes (ionospheric radars)

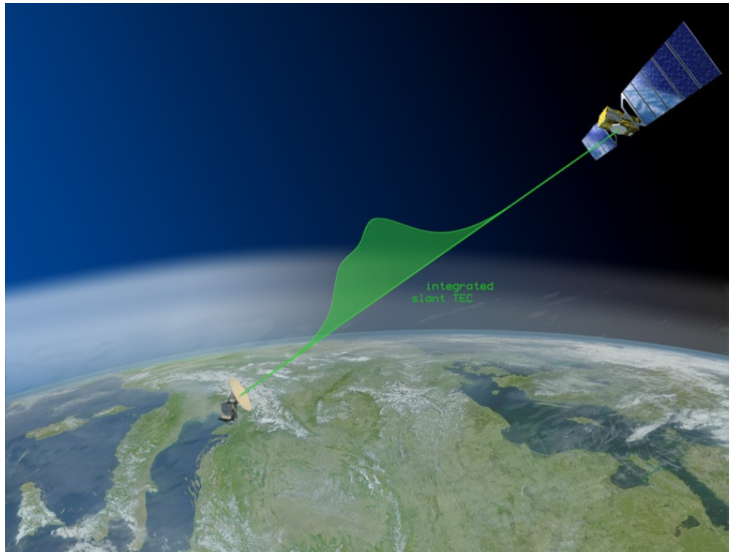




Provide virtual height of the ionosphere as a function of frequency. Bottom side ionosphere electron density profile can be reconstructed using inversion algorithms.

$$h'(f) \longrightarrow N_e(h)$$

Dual frequency GNSS receivers



Total electron content (TEC) is the number of electrons in a column with a cross section of one square meter along the signal path

$$TEC = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)(P_2 - P_1)$$

Motivation

- To mitigate Ionospheric effects in communication or navigation systems, for example GNSS, different classes of Ionospheric models are developed and used
  - Physics-based
  - Empirical or semi-empirical
  - Data assimilative
- All the existing models rely on experimental data obtained mainly by
  - Ionosondes
  - Dual frequency GNSS receivers
  - Rest of the instruments (ISR, in-situ ED, RO etc.)
- Ionosondes (several tens to hundred $k)
  - Digisonde
  - CADI
  - INGV
  - VIPIR (Dynasonde)
- Dual frequency GNSS receivers (several to few tens $k)
  - Septentrio
  - Novatel
  - Leica
  - Trimble
- Can low-cost equipment be used to study the ionosphere?

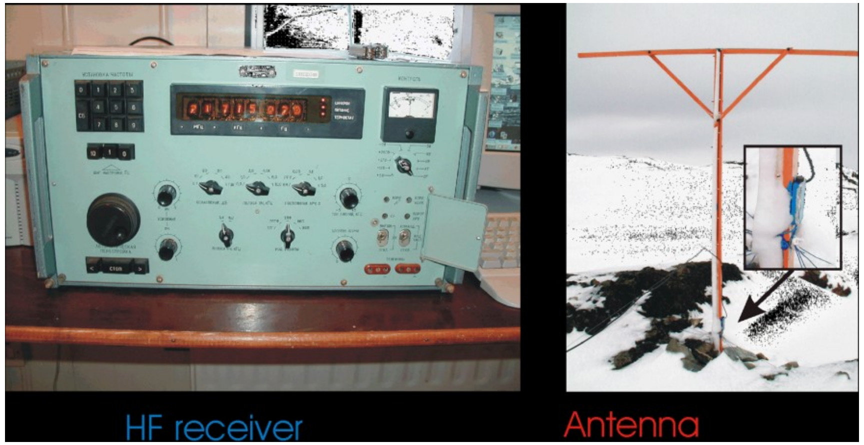
Department of Radiophysics of Geospace, Institute of Radio Astronomy, Ukraine

- Space Weather
  - Ionospheric and magnetospheric research at high and middle latitudes
  - Study of the natural global resonances of the earth-ionosphere waveguide system (e.g. Shumann & Alfven resonances)
  - Development of the new radio physical and radio astronomical methods for remote sensing the geospace, its plasma and field characteristic
- Interplanetary medium
  - Jupiter's sporadic high frequency radio emission research
  - Development of the theoretical models of radio wave propagation

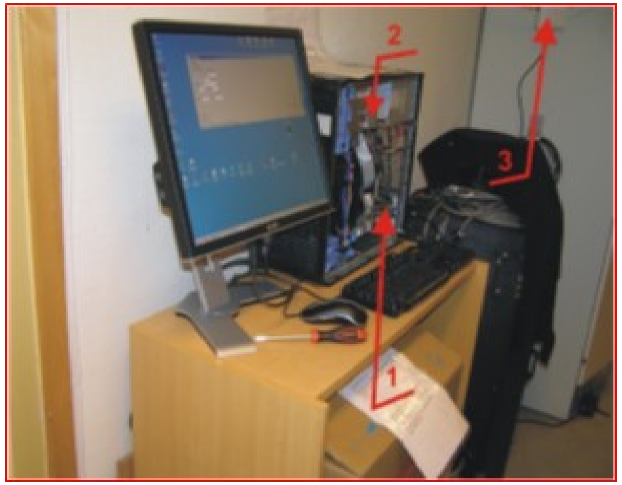
Instruments for HF ionospheric diagnostics: evolution

1990s

2003



2006

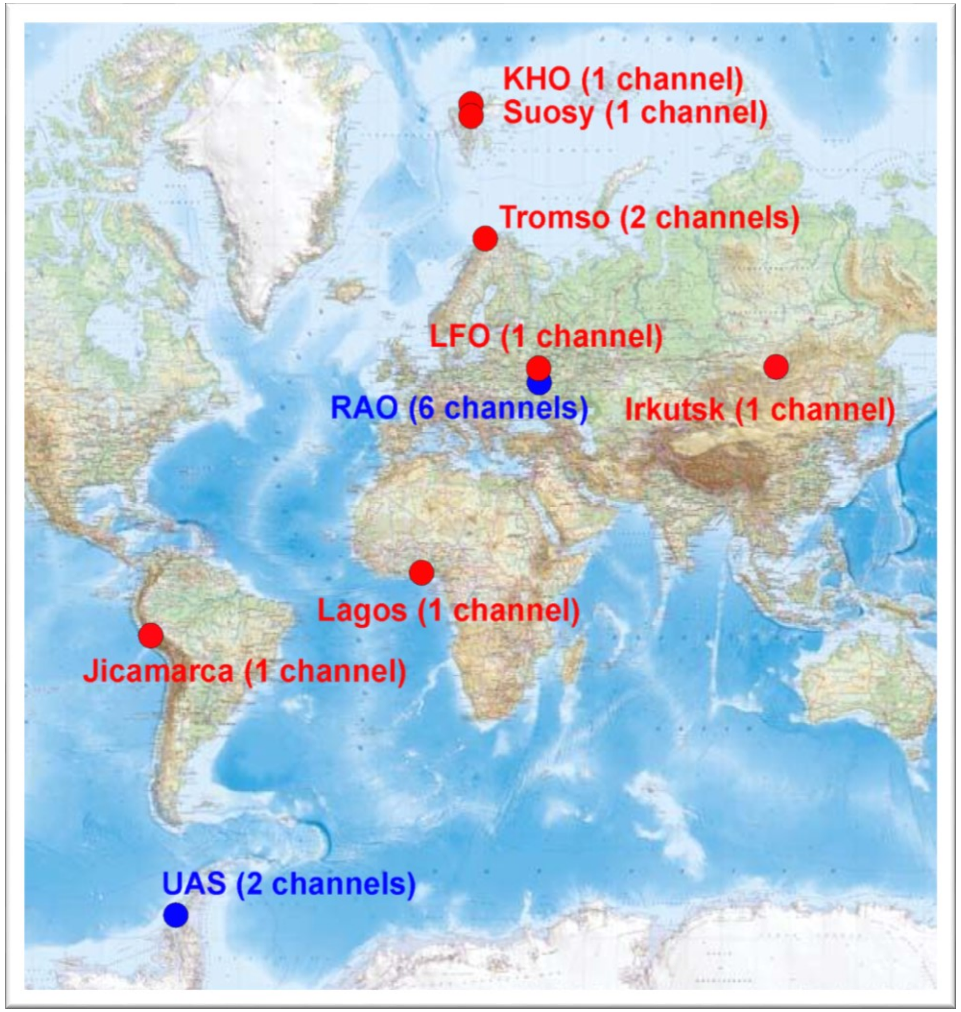


2013

2015

Network of Internet-controlled HF receivers for ionospheric research

- Includes sites in different latitudinal sectors (high, middle, low)
- Both hemispheres
- Controlled remotely via Internet (where available)
- Data is automatically collected on the main server
- Data is processed and presented in the near real-time (1-3 hour latency)
- Used to receive HF signals of different origins: broadcasting stations, signals from dedicated transmitters, signals of HF heaters, e.g. like HAARP, Tromso, SURA

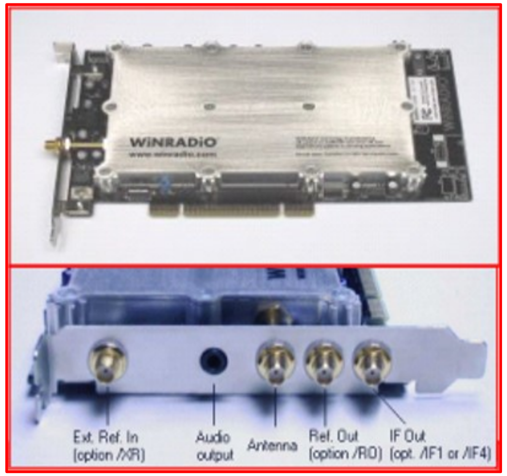


Koloskov, A. V., Y. M. Yampolski , A. V. Zalizovsky, V. G. Galushko , A. S. Kashcheev, C. La Hoz, A. Brekke, V. Belyey, M. T. Rietveld, Network of Internet-controlled HF receivers for ionospheric researches, 2014, Radio Physics and Radio Astronomy, Vol. 19, p. 324, https://doi.org/10.15407/rpra19.04.324

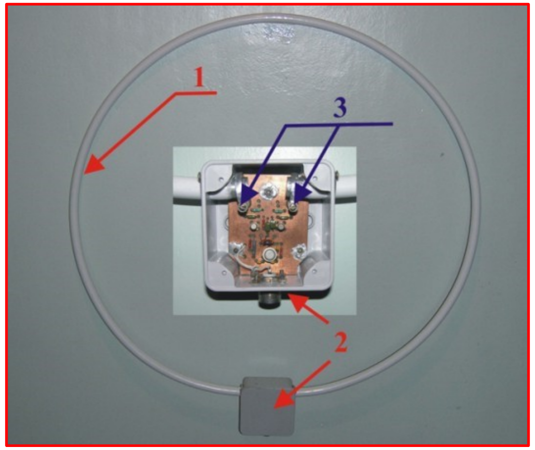
Low-cost software defined HF Doppler receiver

- Winradio G313i receiver (DSP-based)
- High accuracy Doppler shift measurements (long-term stability ~ 10 ppb per day) with external RO
- High sensitivity (0.07μV CW)
- Small size active loop antenna
- Fully automated and remotely controlled
- Low-cost, software-defined*

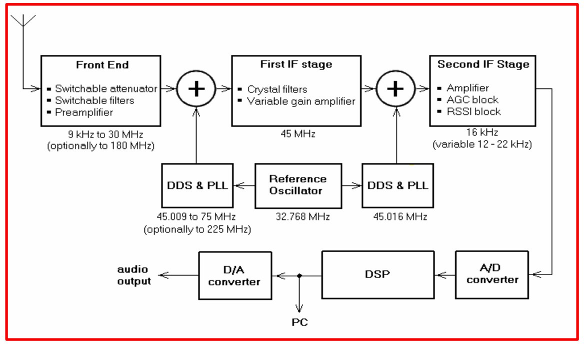
Receiver board



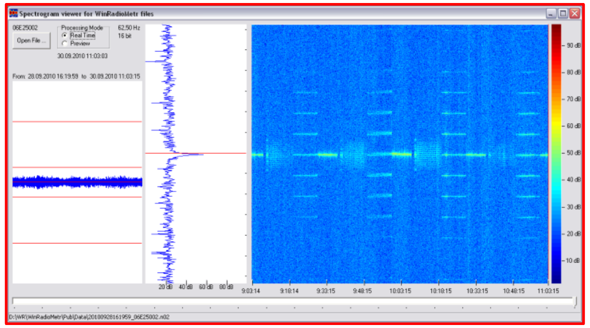
Loop antenna & amplifier



Functional diagram



Monitoring software



06E25002

Processing Mode
● Real Time
○ Preview

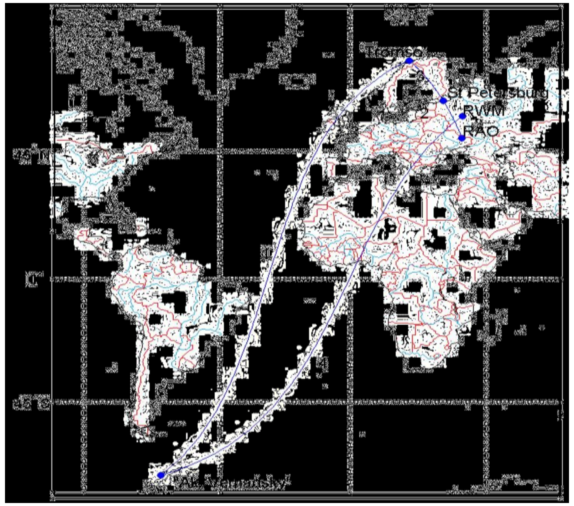
62.50 Hz
16 bit

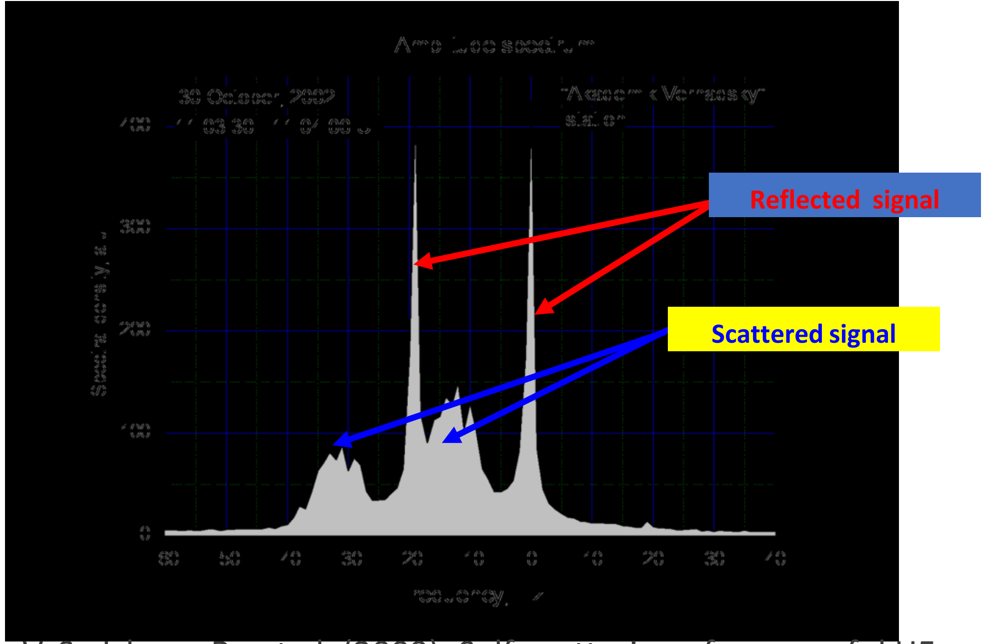
30.09.2010 11:03:03

From: 28.09.2010 16:19:59 to 30.09.2010 11:03:15

Low-cost software defined HF Doppler receiver: examples of research

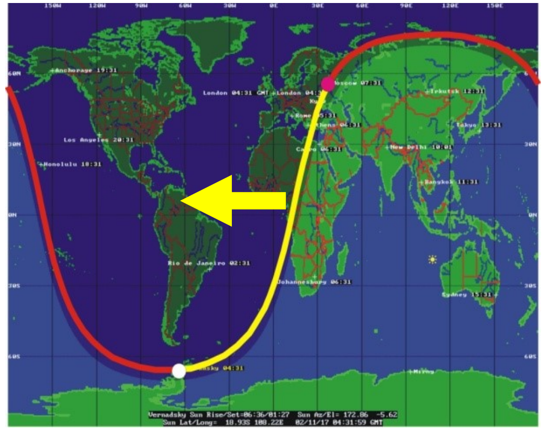
Self-scattering effect of powerful HF radio wave

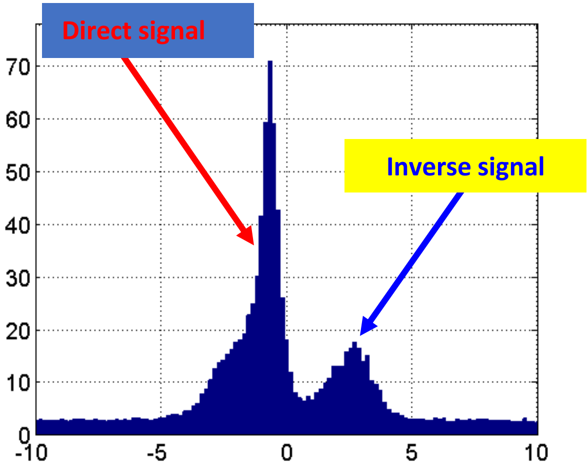


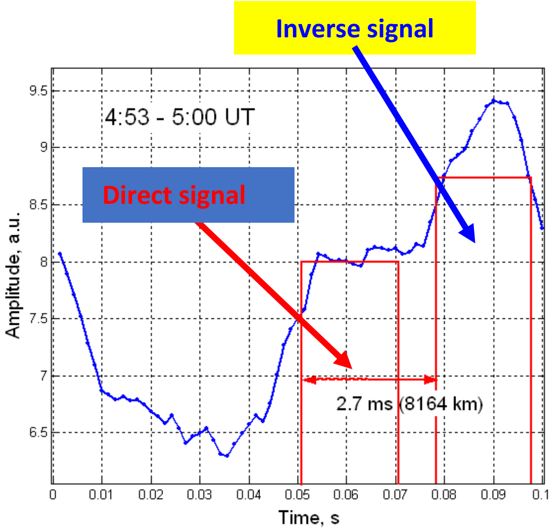


Zalizovski, A. V., Kashcheyev, S. B., Yampolski, Y. M., Galushko, V. G., Belyey, V. S., Isham, B., et al. (2009). Self-scattering of a powerful HF radio wave on stimulated ionospheric turbulence. Radio Sci. 44, 241–253. doi: 10.1029/2008RS004111

Long distance propagation along solar terminator path





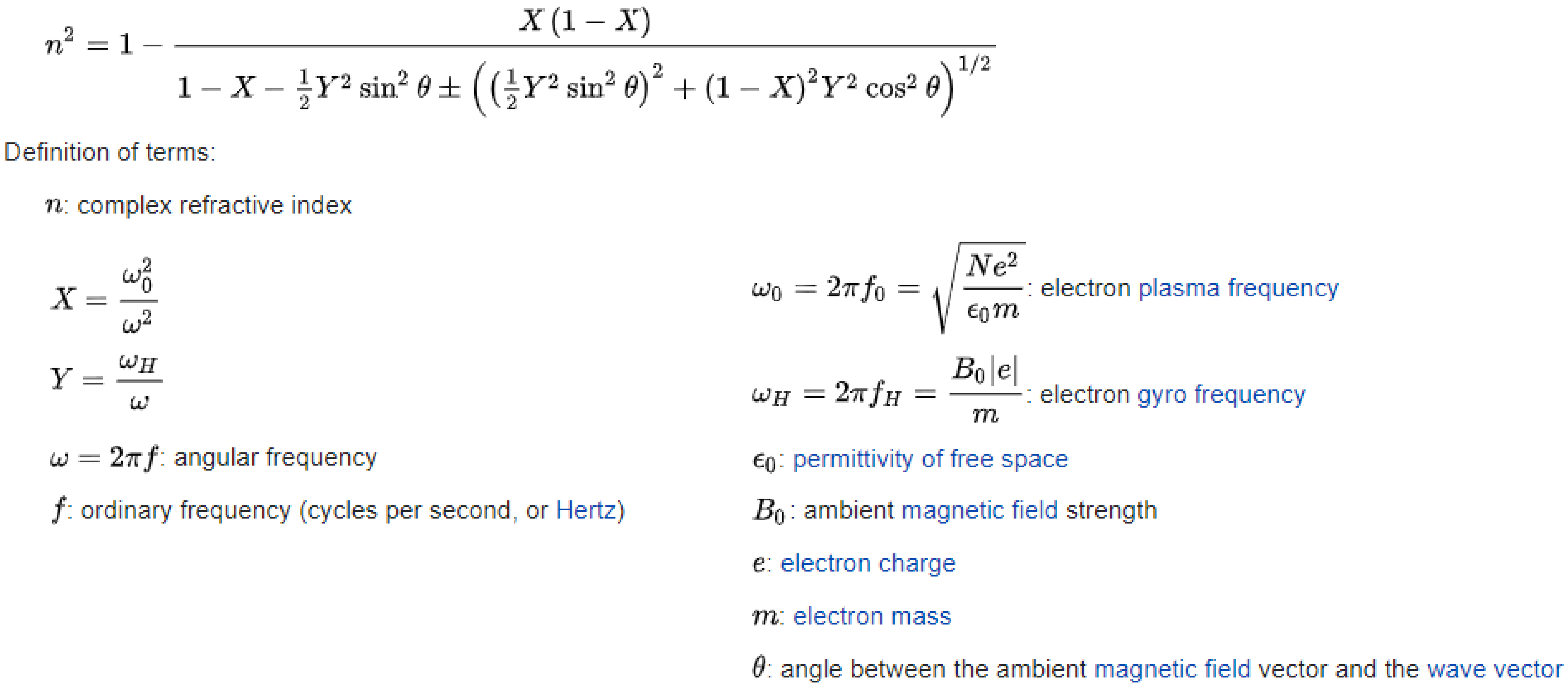


Zalizovski, A. V., Koloskov, A. V. and Yampolski, Y. M. (2015). Studying in Antarctica the time-frequency characteristics of HF signals at the long radio paths. Ukrainian Antarctic Journal, No. 14, pp. 124–137

Low-cost software defined HF Doppler receiver: examples of research

Occurrence characteristics of ULF waves in Nigeria

Appleton–Hartree equation defining the refractive index



$$n^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2\sin^2\theta \pm \left(\left(\frac{1}{2}Y^2\sin^2\theta\right)^2 + (1-X)^2 Y^2\cos^2\theta\right)^{1/2}}$$

Definition of terms:

n: complex refractive index

$X = \frac{\omega_0^2}{\omega^2}$

$Y = \frac{\omega_H}{\omega}$

$\omega = 2\pi f$: angular frequency

f: ordinary frequency (cycles per second, or Hertz)

$\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\epsilon_0 m}}$: electron plasma frequency

$\omega_H = 2\pi f_H = \frac{B_0|e|}{m}$: electron gyro frequency

ϵ_0: permittivity of free space

B_0: ambient magnetic field strength

e: electron charge

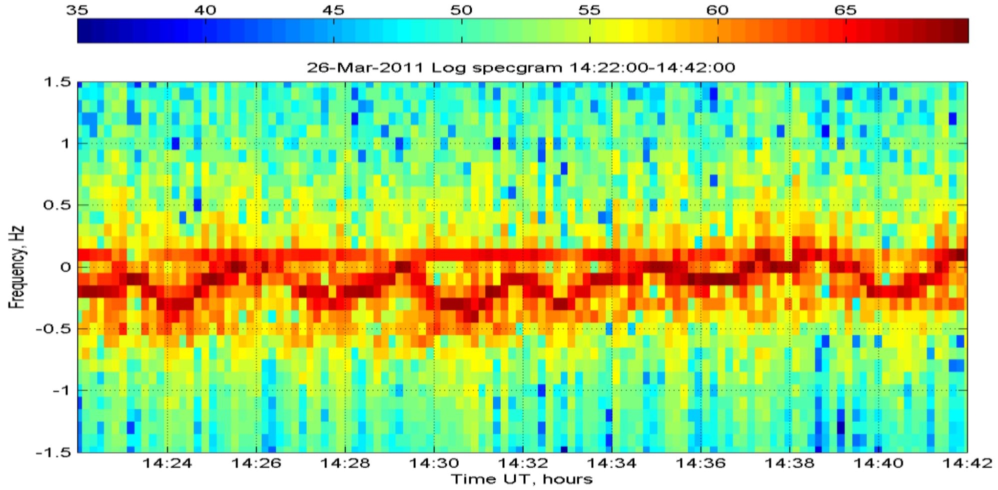
m: electron mass

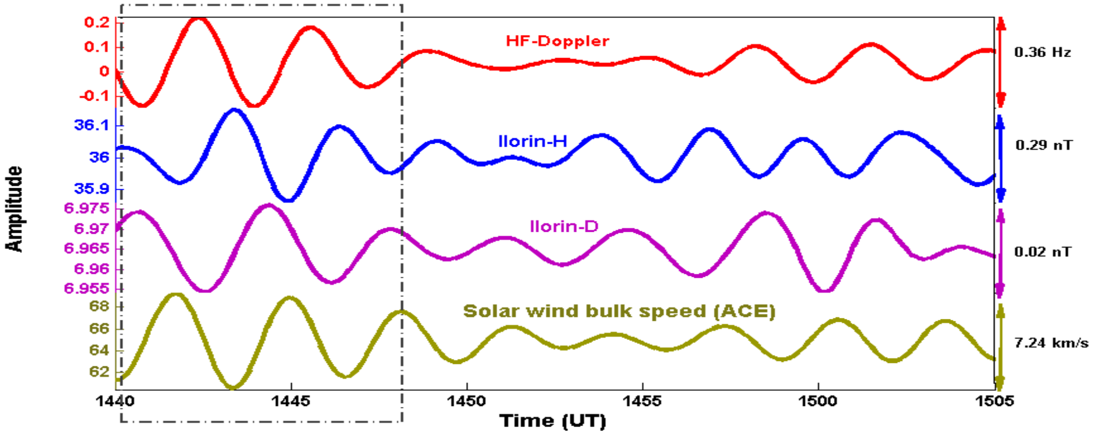
θ: angle between the ambient magnetic field vector and the wave vector

Low-cost software defined HF Doppler receiver: examples of research

Occurrence characteristics of ULF waves in Nigeria

7.257 MHz, Federal Radio Corporation of Nigeria (FRCN), Abuja

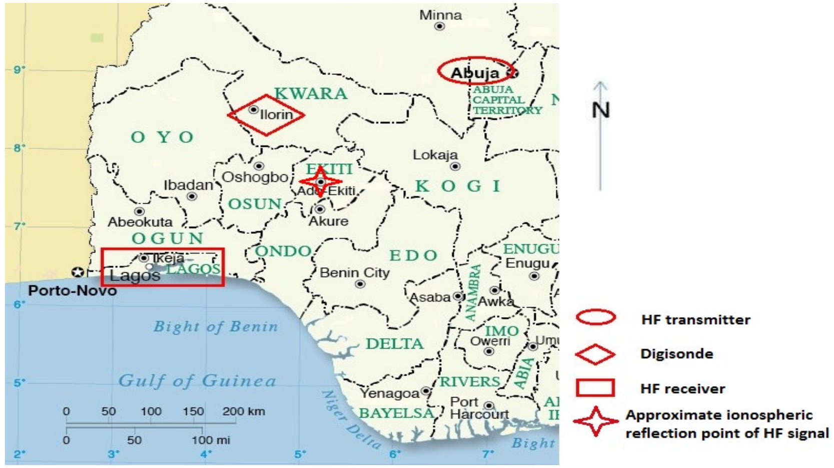


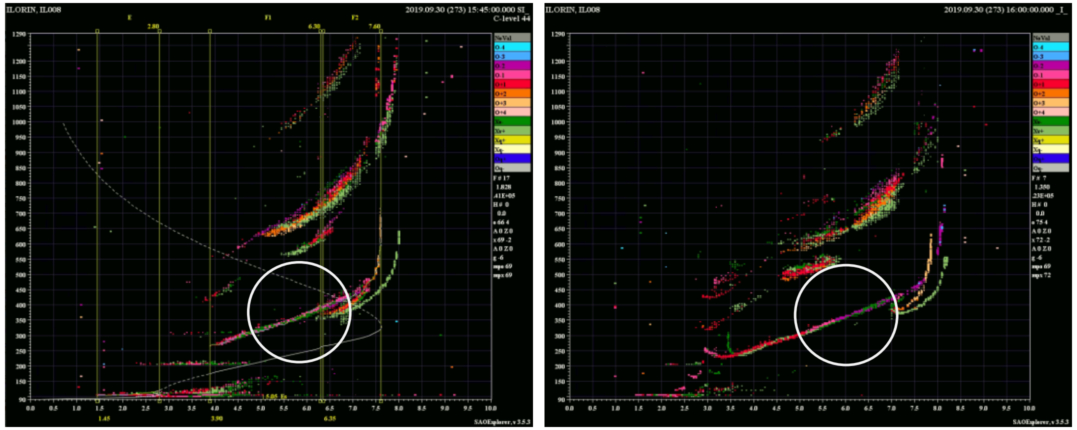


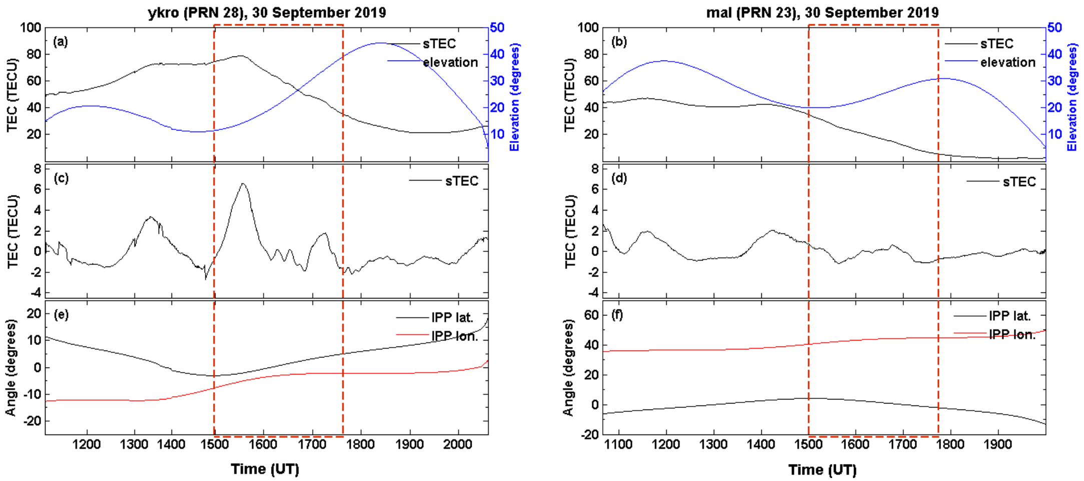
Credits: B. Olugbon, E.O. Oyeyemi, University of Lagos

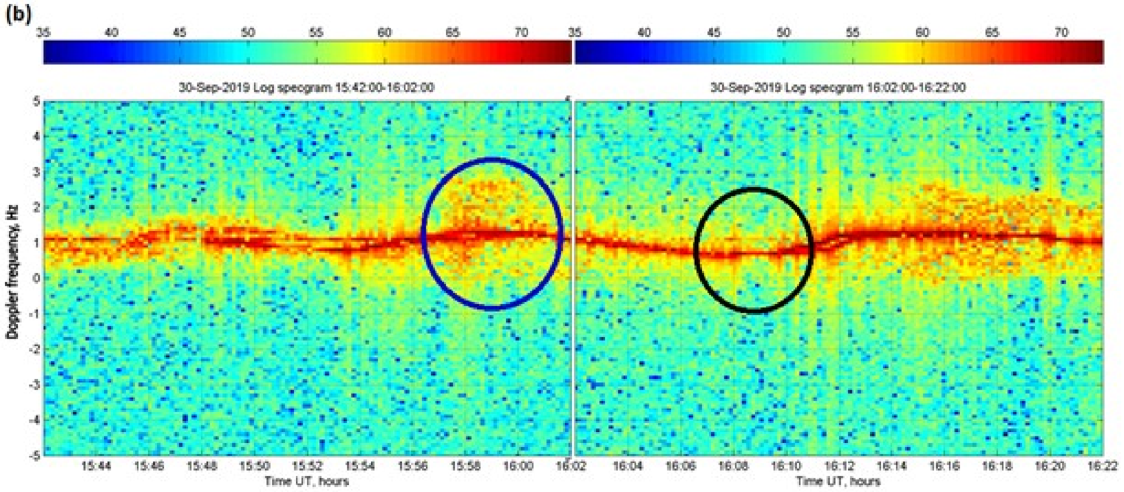
Low-cost software defined HF Doppler receiver: examples of research

Daytime Equatorial Spread-F/TIDs registered by Digisonde, HF Doppler & GNSS receivers (work in progress)









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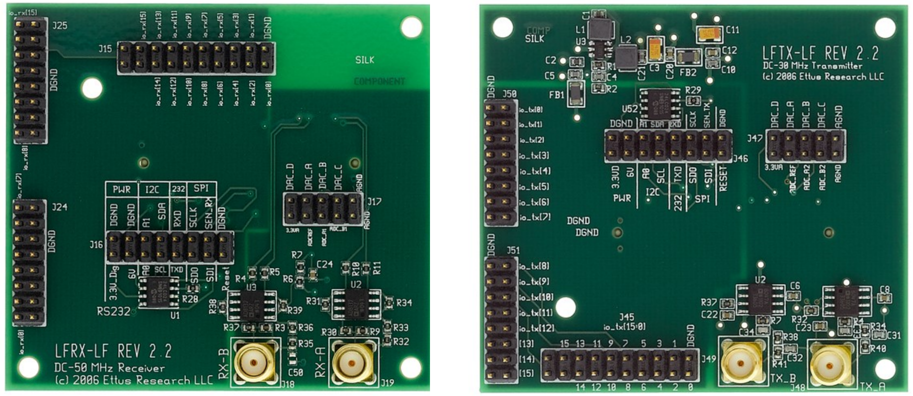
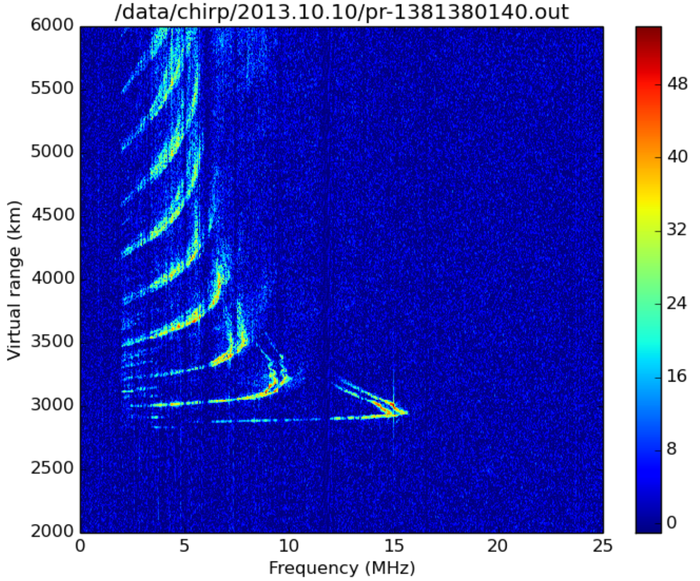
Low-cost software defined radio: USRP N-200/210

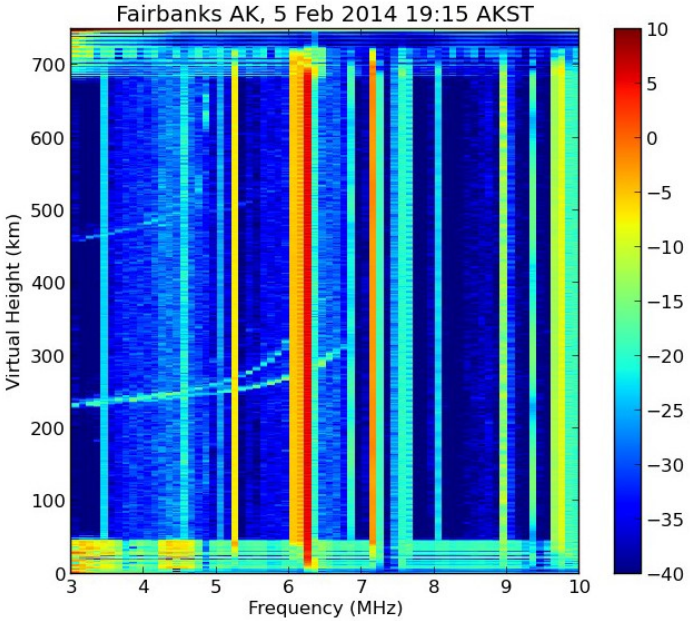
- Fully software-defined radio (Spartan FPGA-based)
- Direct conversion receiver/transmitter (no hardware intermediate frequencies)
- Dual 100 MS/s, 14-bit ADC
- Dual 400 MS/s, 16-bit DAC
- Up to 50 MS/s Gigabit Ethernet Streaming
- UHD drivers (open source available via Github)
- Supports different daughterboards (in our case they are LFRX and LFTX, 0-30 MHz)
- Supports external reference oscillator and PPS signal input



USRP-based experiments

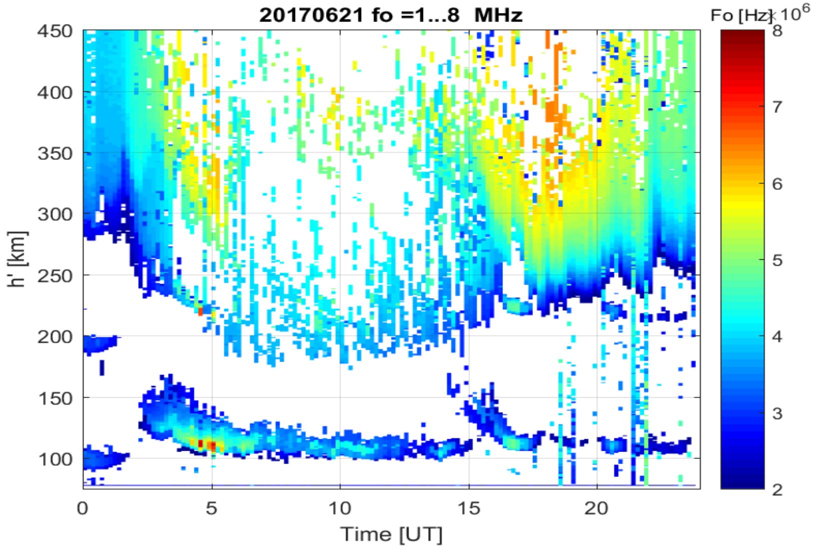
- GNU Chirp sounder, Yuha Vierinen (https://www.sgo.fi/~j/gnu_chirp_sounder)
    - Software defined radio-based receiver for monitoring ionospheric sounders (ionosondes) and over-the-horizon radars that use linear frequency sweep FM-CW transmissions
    - Based on gnuradio and relies on Ettus research USRP2 and USRP N210 based digital receivers
    - The receiver can be used to receive the whole HF band (typically at 25 MHz bandwidth) simultaneously, and to receive multiple sounders simultaneously
- Design of a flexible and low-power ionospheric sounder, Alex Morris, M.S. Thesis (https://scholarworks.alaska.edu/handle/11122/4535)
    - USRP-N200 based ionospheric sounder
    - Active magnetic loop antenna
    - Peak transmit power 10W
    - Barker code

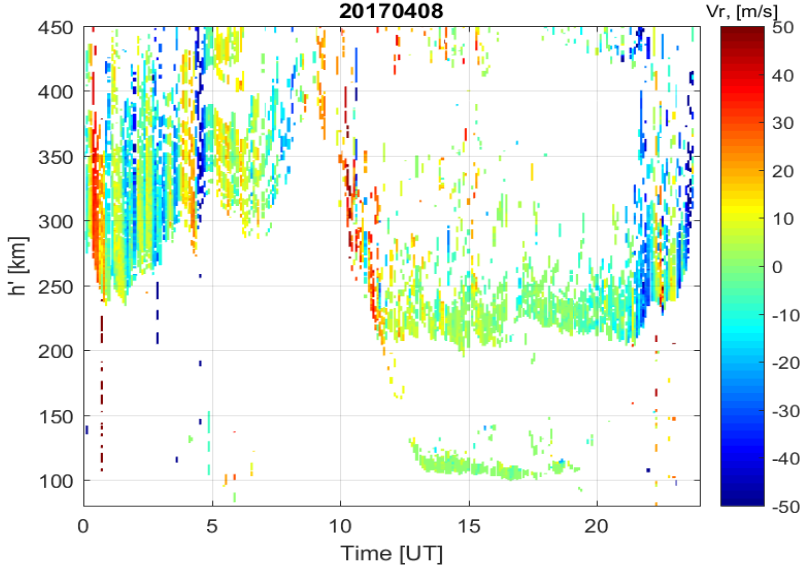




USRP-based ionospheric sounder

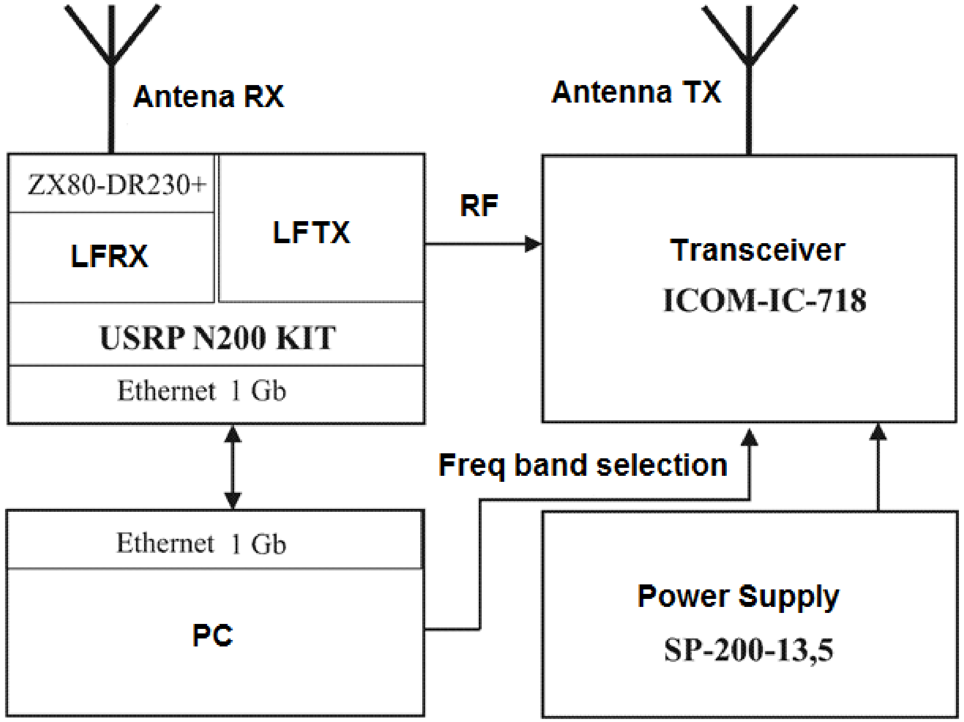
- Software defined radio (SDR) based (USRP N200)
- HF communication transceiver used as an amplifier (ICOM 718)
- Frequency range: 1.6 – 30 MHz
- Peak power: 100 W (~10W average)
- Complementary code (16-128 bits)
- Time to produce one ionogram: 1-3 min
- PC based signal generation and processing
- Ionograms (virtual height measurements)
- Dopplerograms (plasma velocity measurements)
- Height-time intensity and Doppler sky-maps
- Total cost: ~$5k





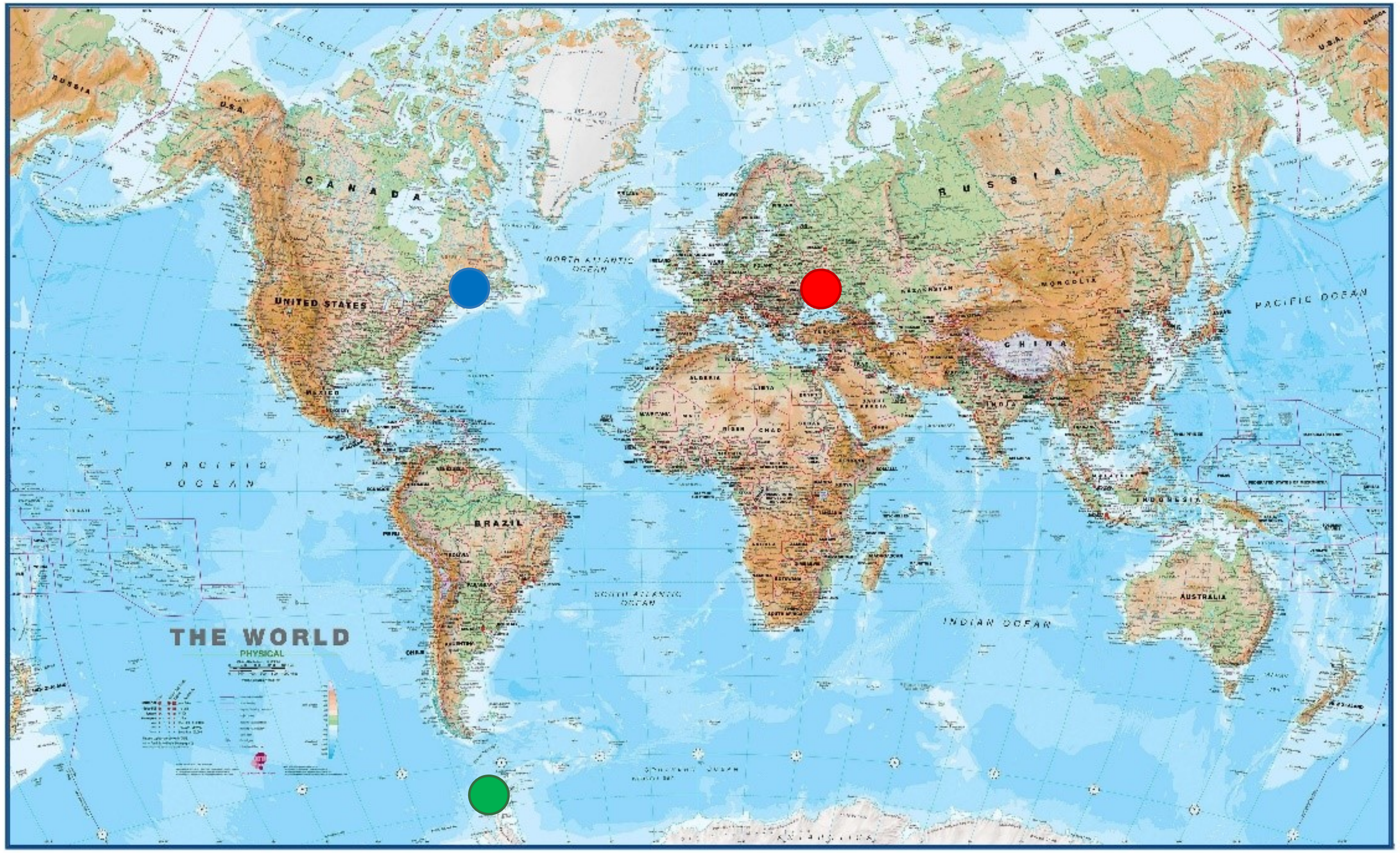
Zalizovski, A.V., Kashcheiev, A.S., Kashcheiev, S.B., Koloskov, A.V., Lisachenko, V.N., Paznukhov, V.V., Pikulik, I., Sopin, A.A., Yampolski, Yu.M., A prototype of a portable coherent ionosonde, Space Sci.&Technol. 2018, 24 ;(3):10-22, https://doi.org/10.15407/knit2018.03.010

USRP-based ionospheric sounder, block diagram



Credits: Koloskov, A

USRP-based ionospheric sounder, field tests

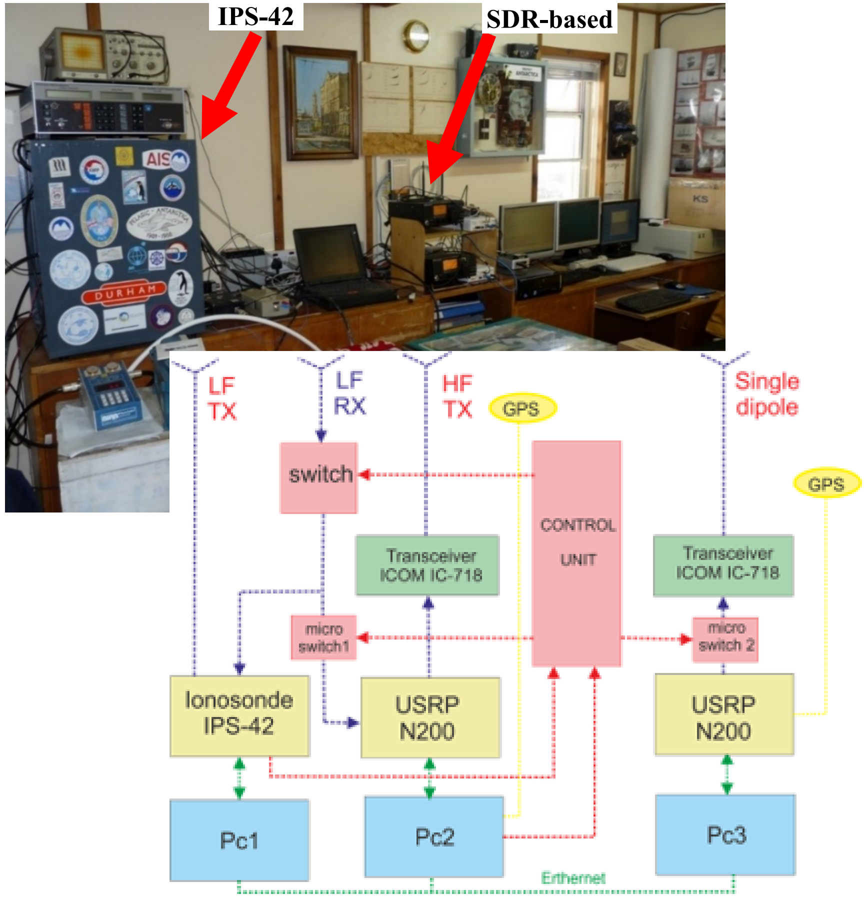


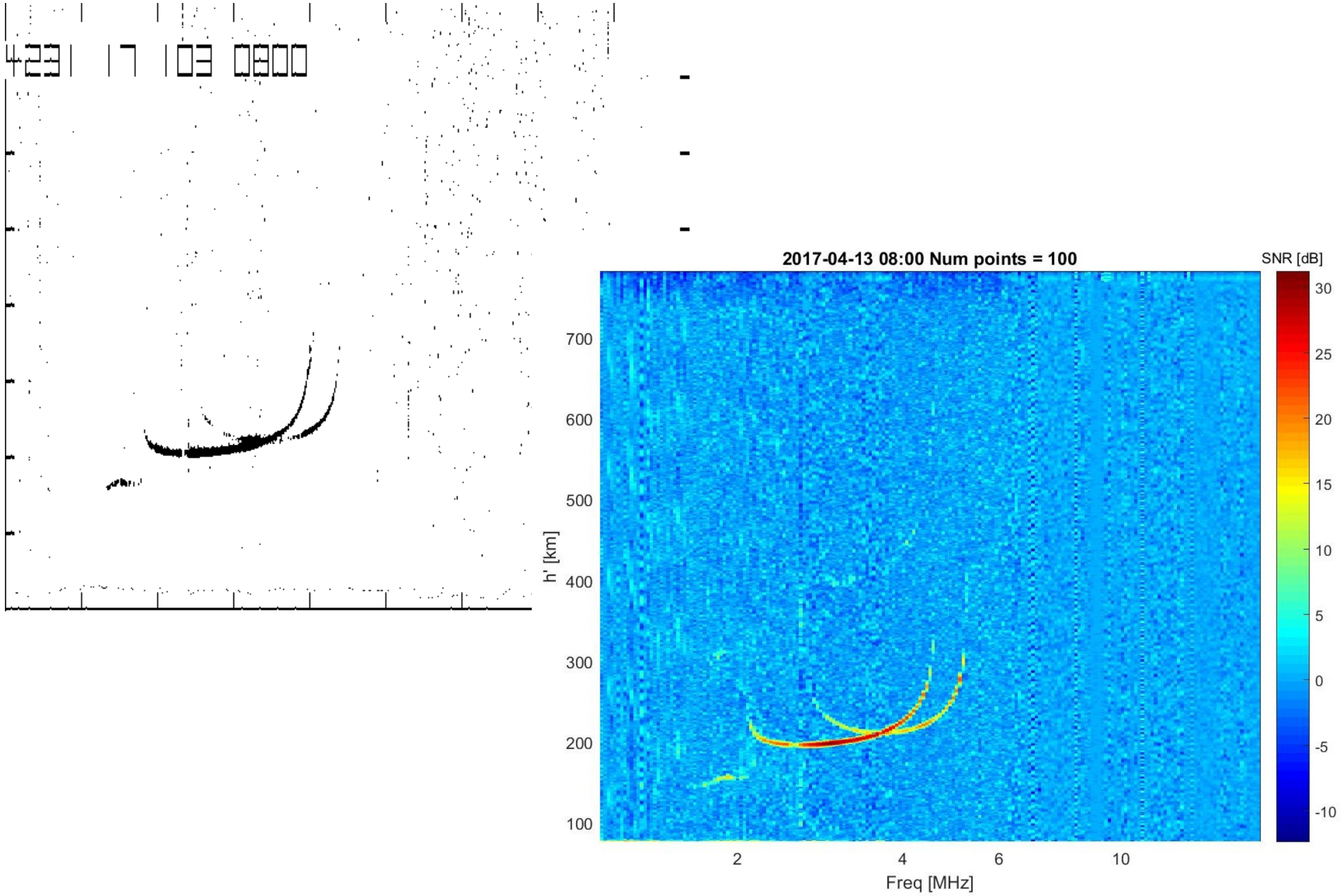
- 🟢 Research Base “Ak Vernadksy”, Antarctica (Apr 2017)
- 🔴 Kharkiv, Ukraine (Dec 2017)
- 🔵 Blissville, Canada (Dec 2019)

USRP-based ionospheric sounder, data comparison

Research base “Ak Vernadsky” IPS-42 vs SDR-based

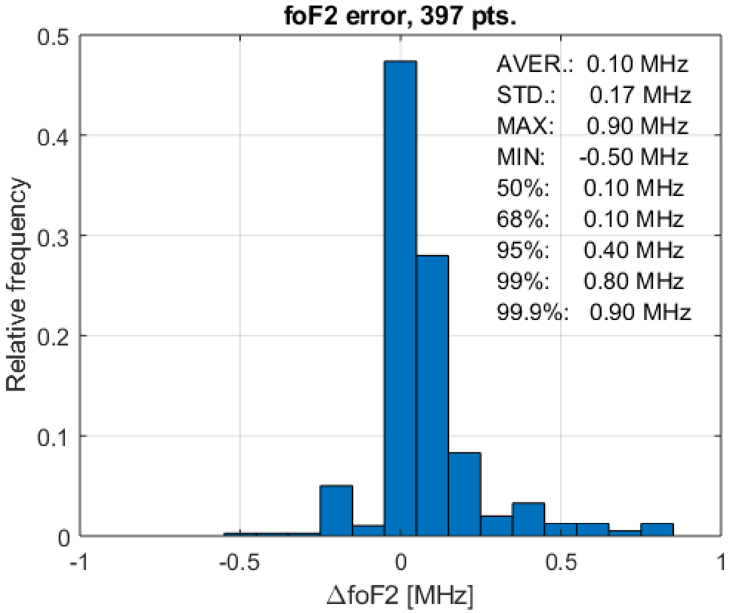
3.5 kW vs 0.1 kW

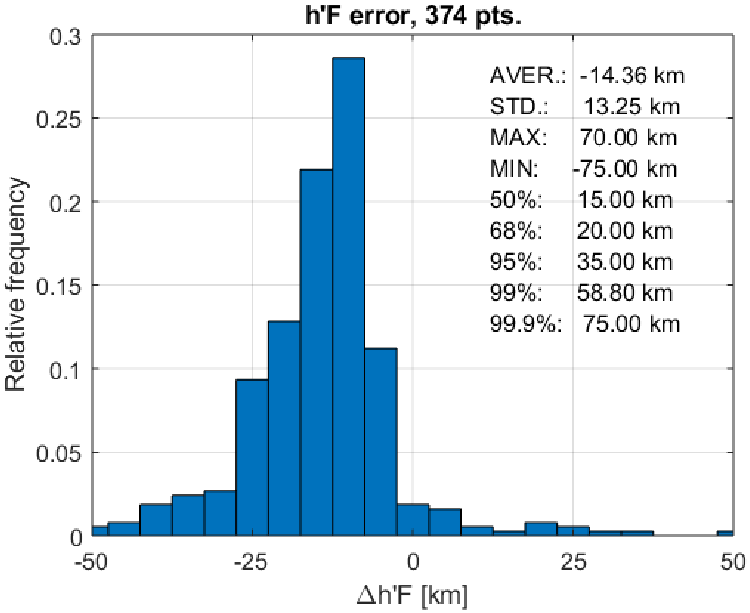


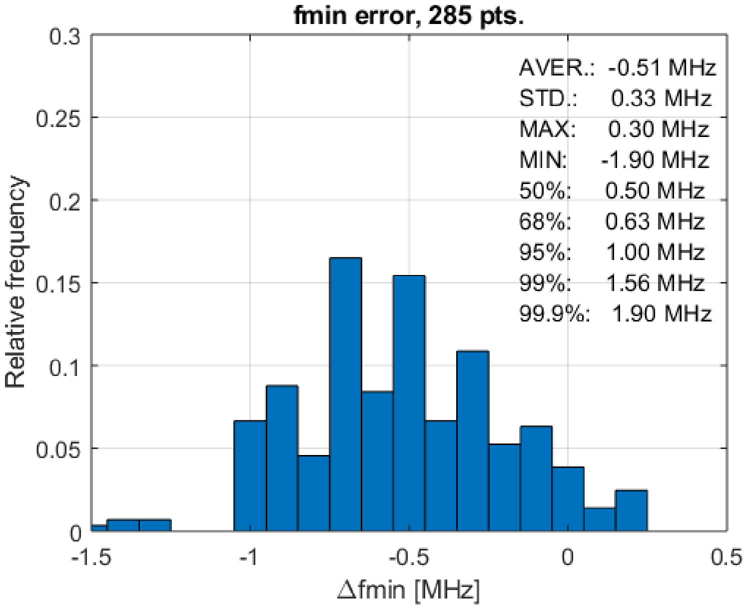


USRP-based ionospheric sounder, comparison statistics

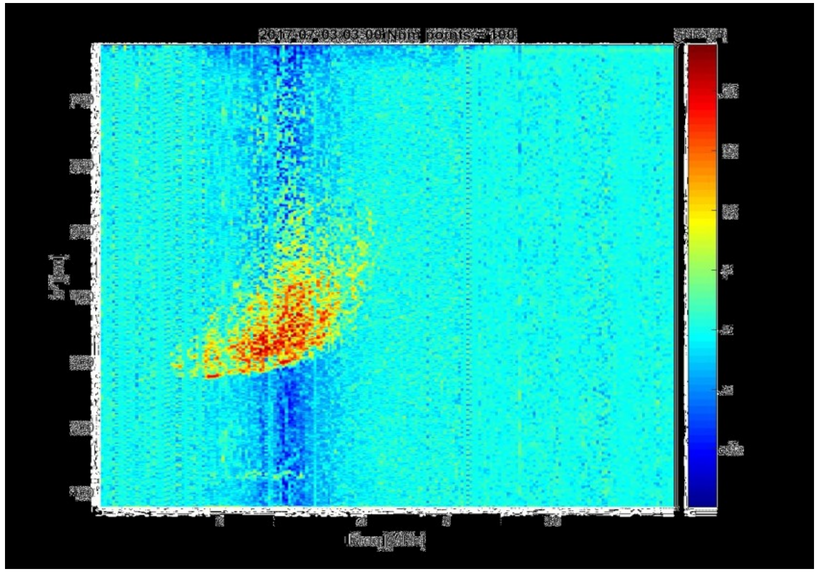
July 2017, manually scaled ionograms

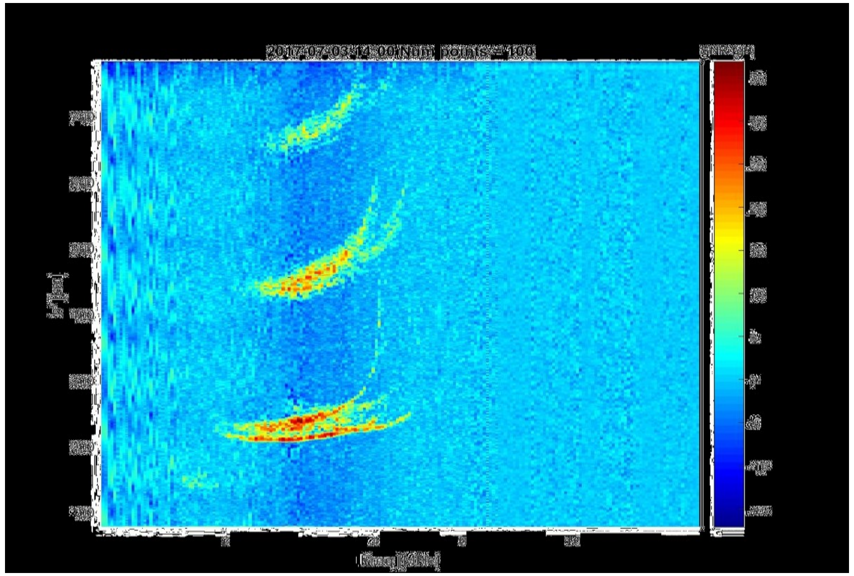




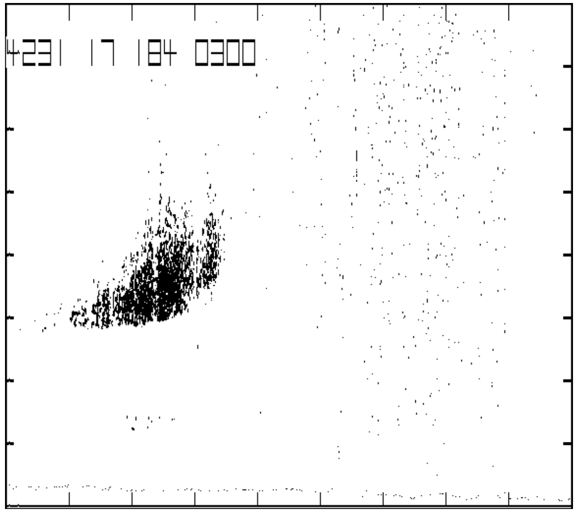


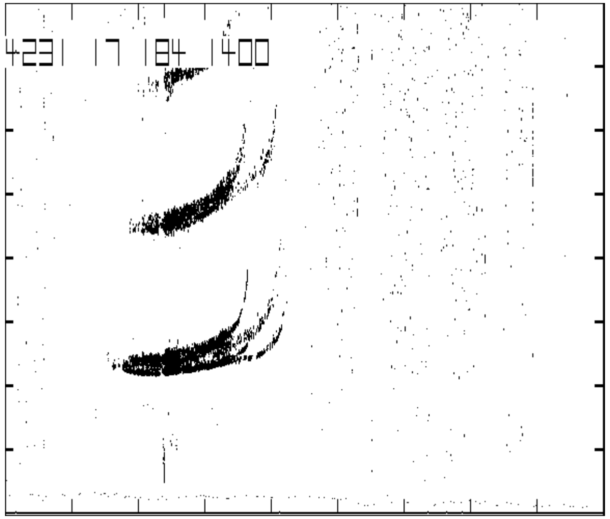
USRP-based ionospheric sounder, ionogram examples





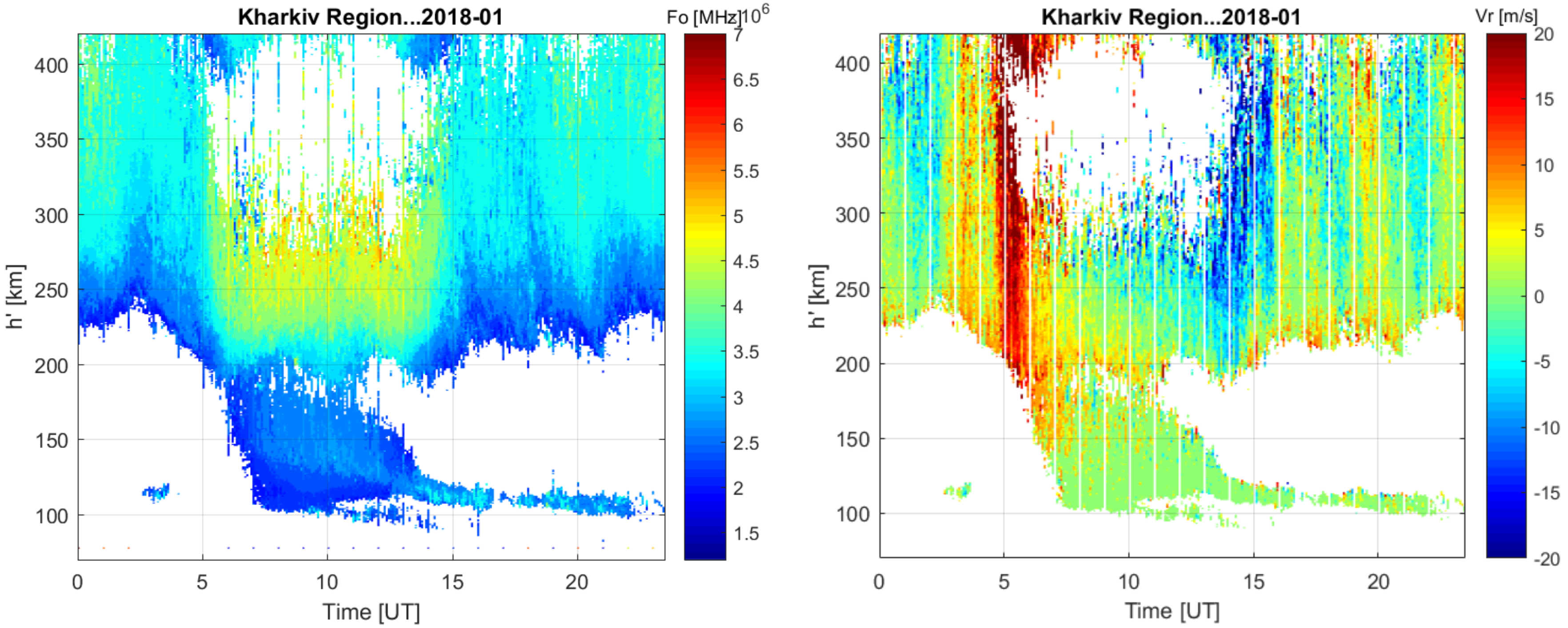
July 2017





USRP-based ionospheric sounder, byproducts

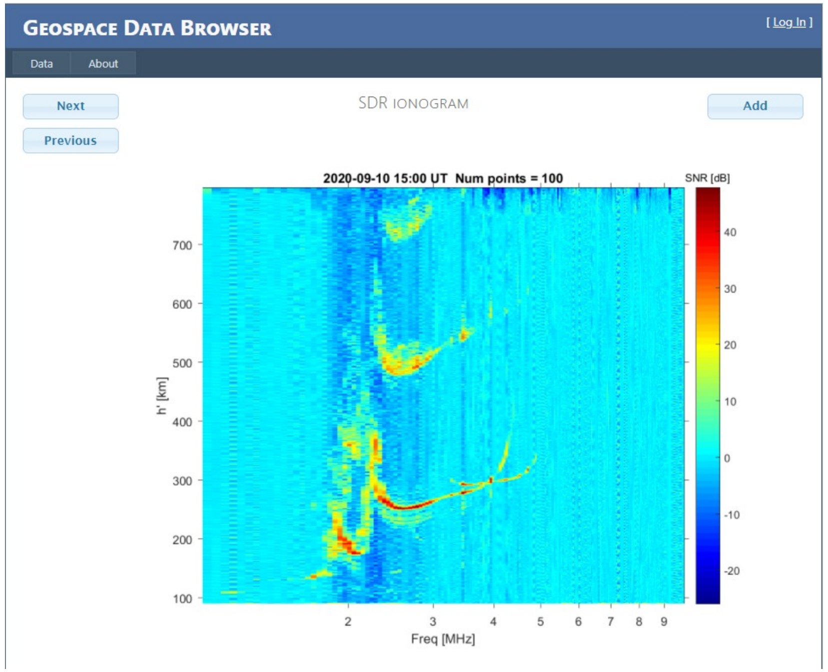
Height-time diagrams of plasma frequency and vertical velocity (monthly median values)



Zalizovski, A., Koloskov, O., Kashcheyev, A., Kashcheyev, S., Yampolski, Y., et al. (2020), Doppler vertical sounding of the ionosphere at the Akademik Vernadsky station., Ukrainian Antarctic Journal, (1), 56-68

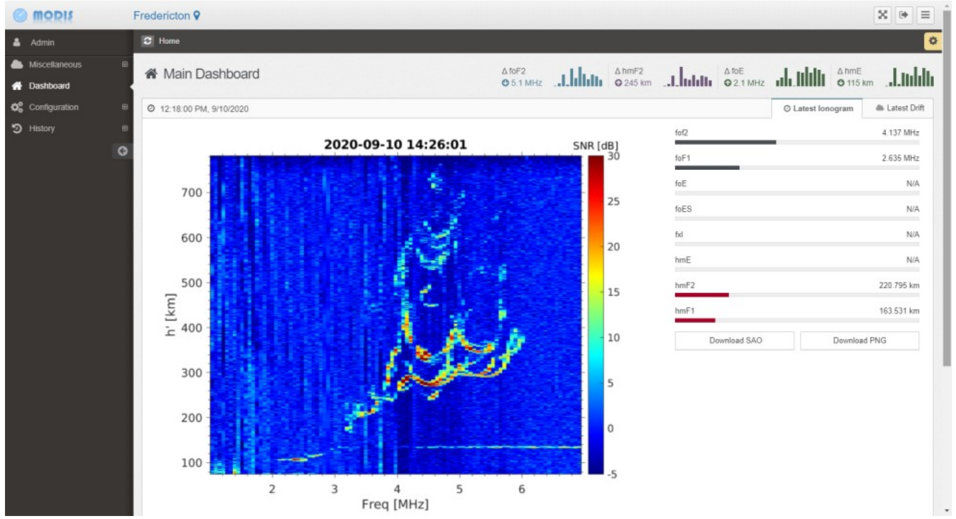
USRP-based ionospheric sounder, online

- Kharkiv, Ukraine



http://geospace.com.ua/databrowser/Default.aspx?observatory=20&instrument=21&datatype=58

- Blissville, Canada

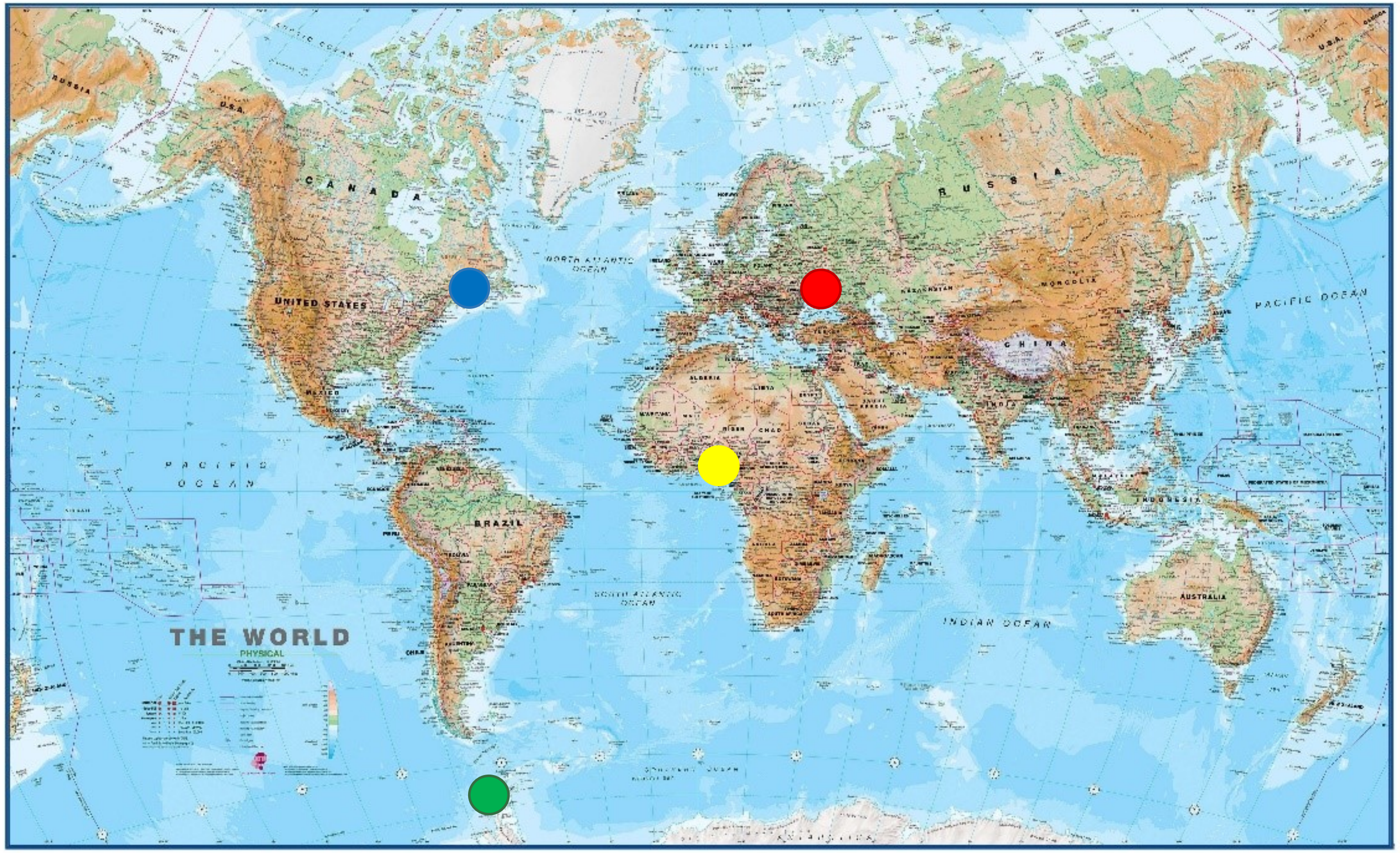


12:18:00 PM, 9/10/2020

fof2 4.137 MHz
foF1 2.635 MHz
foE N/A
foES N/A
fxl N/A
hmE N/A
hmF2 220.795 km
hmF1 163.531 km

http://chain-new.chain-project.net:3000

USRP-based ionospheric sounder, network?



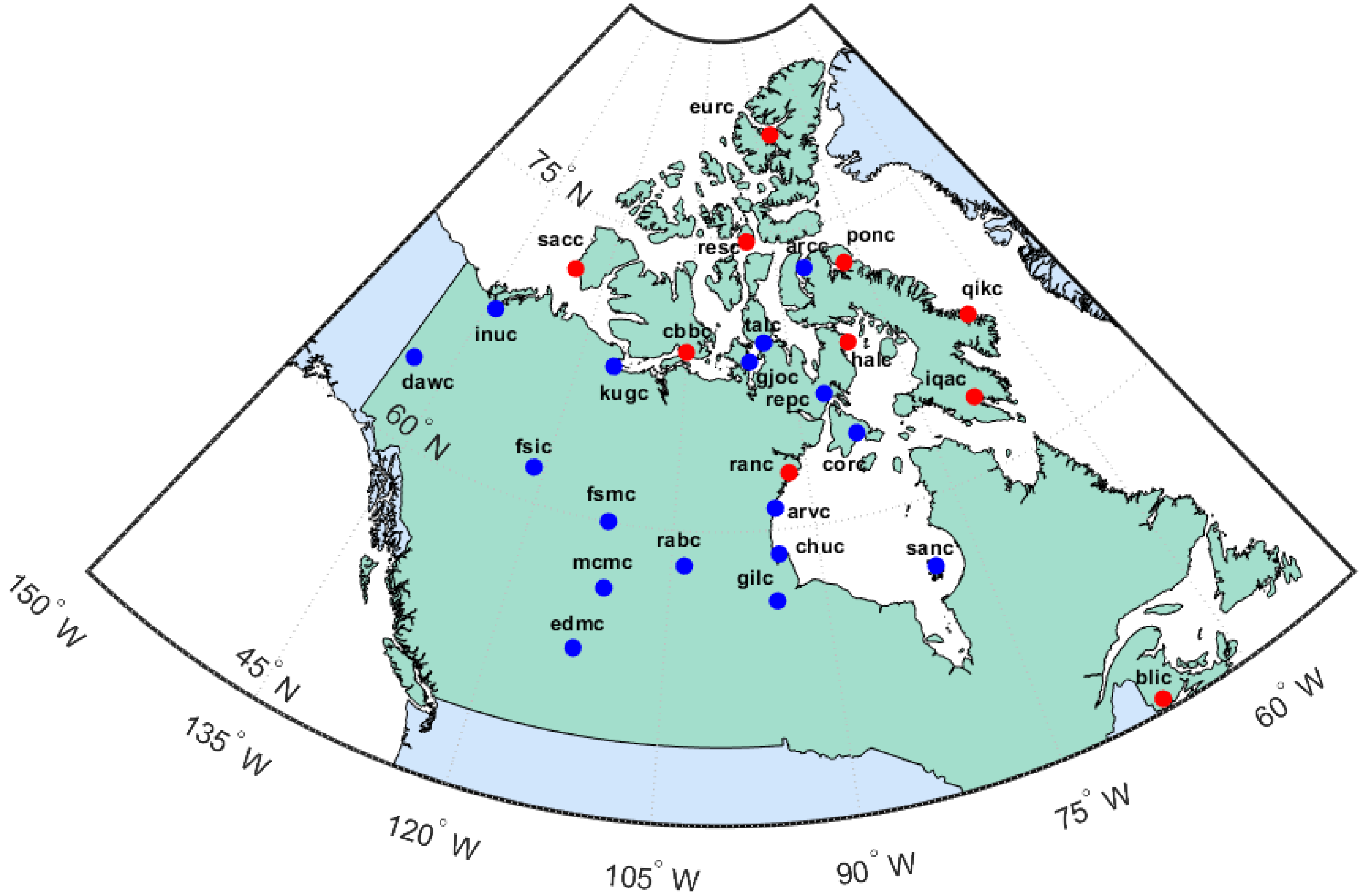
- 🟢 Research Base “Ak Vernadksy”, Antarctica (Apr 2017)
- 🔴 Kharkiv, Ukraine (Dec 2017)
- 🔵 Blissville, Canada (Dec 2019)
- 🟡 Abuja, Nigeria (2021 ?)

CHAIN rk)

http://chain.

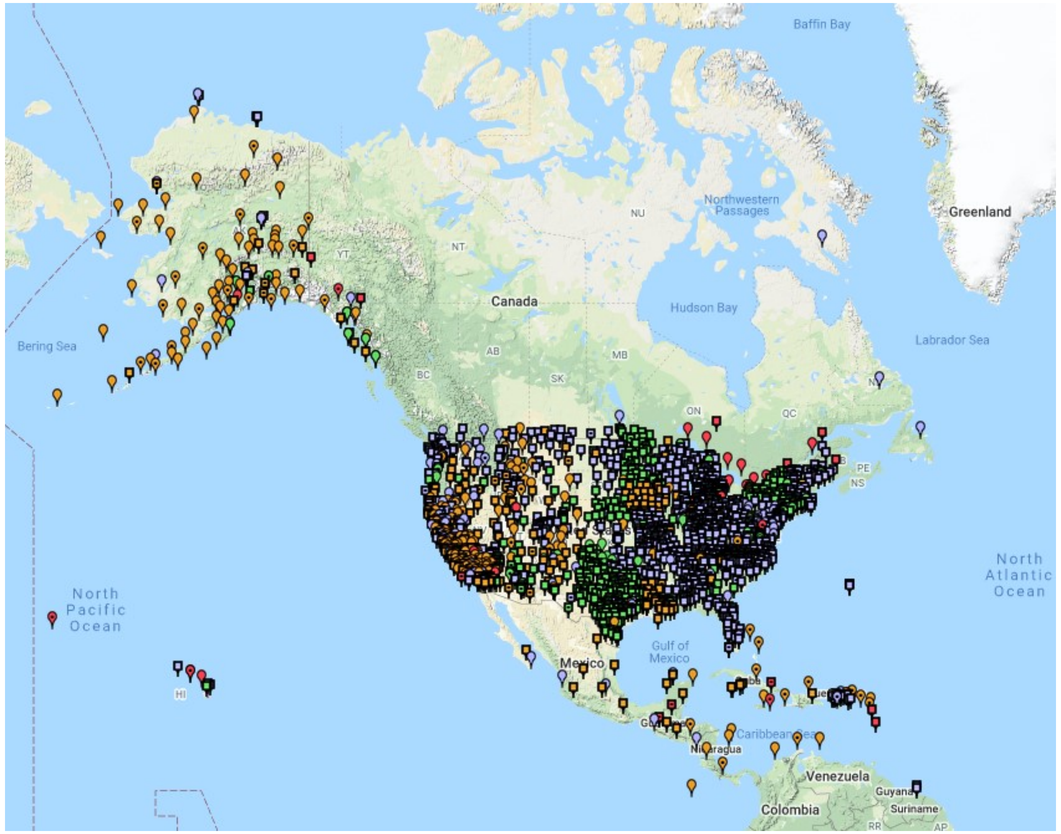
- 28 GNSS I
  Monitor (
  - 19 Sep
  - 9 Nova

GS



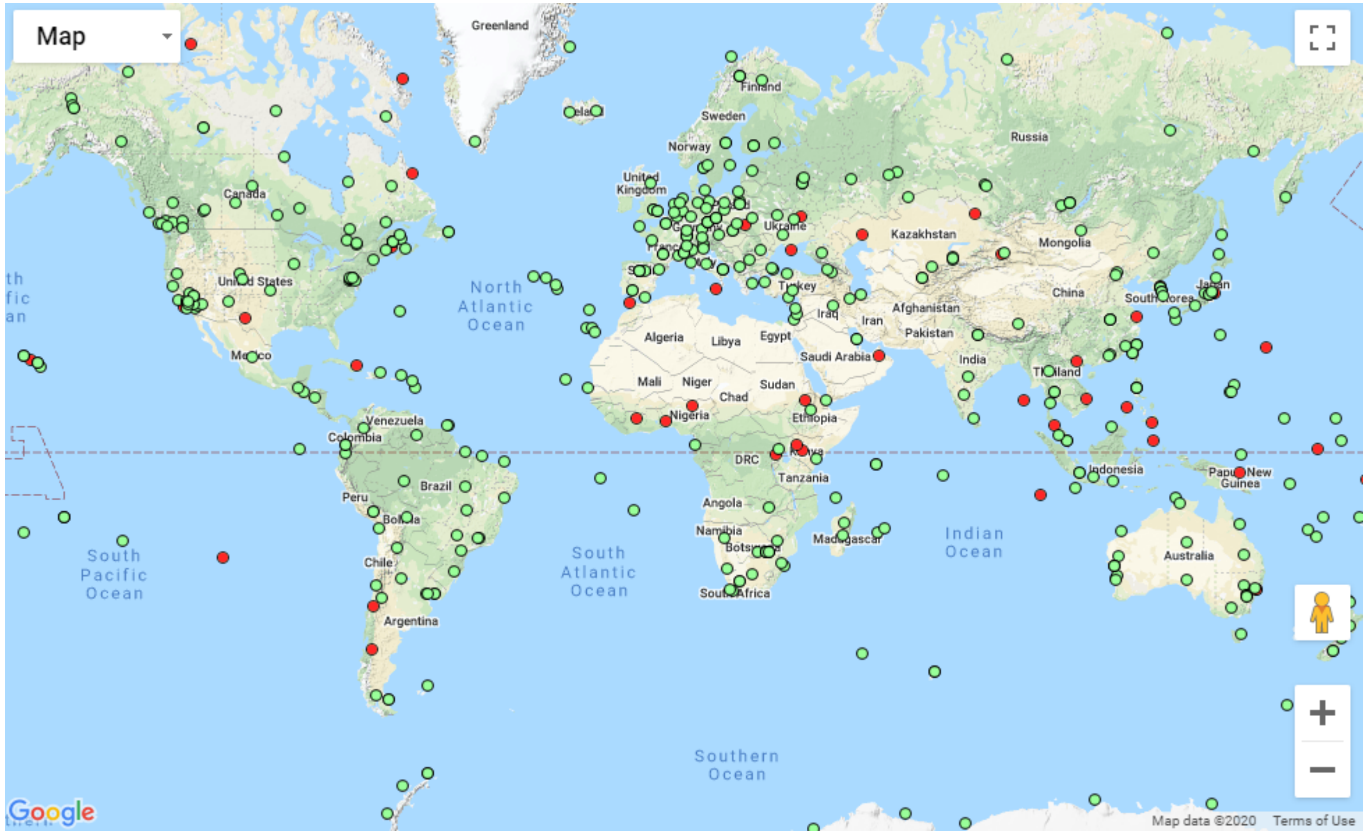
Other Networks

CORS (Continuously Operating Reference Station)



https://www.ngs.noaa.gov/CORS/

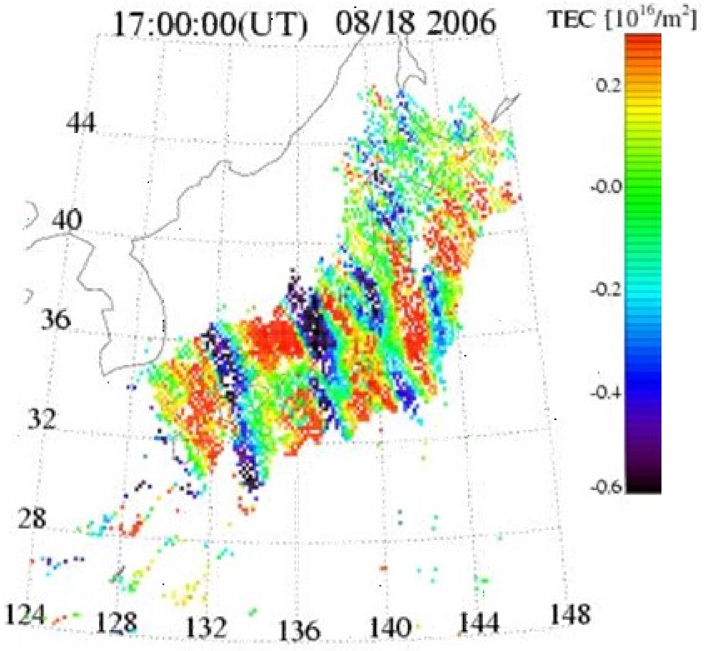
IGS (International GNSS Service)



http://www.igs.org/network

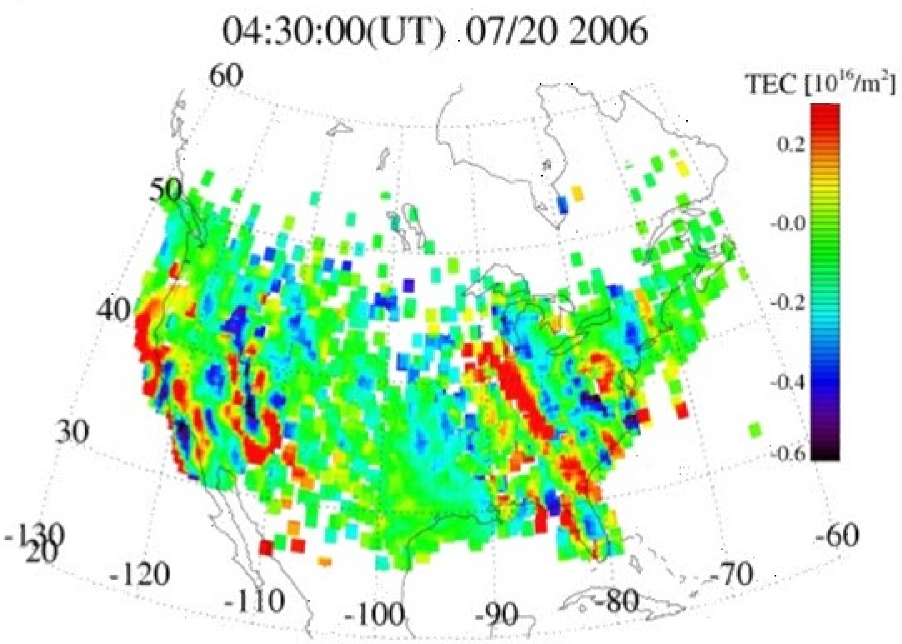
Case Studies: MSTIDs

Japan



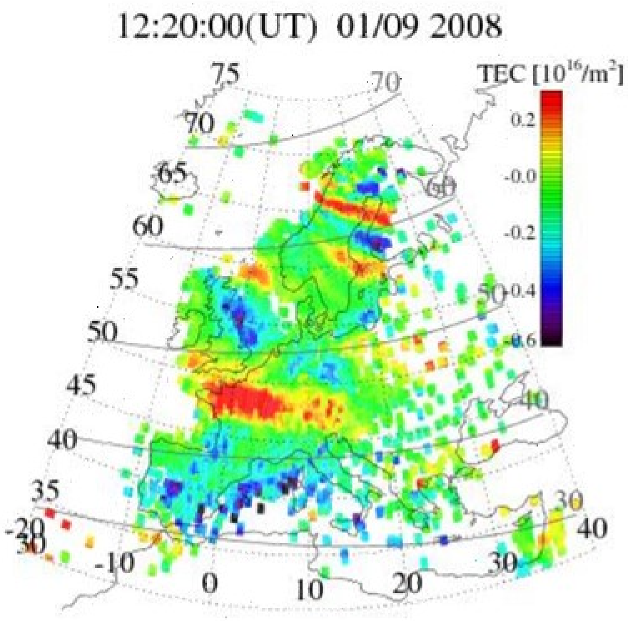
Tsugawa, T., Kotake, N., Otsuka, Y. et al. Medium-scale traveling ionospheric disturbances observed by GPS receiver network in Japan: a short review. GPS Solut 11, 139–144 (2007)

USA



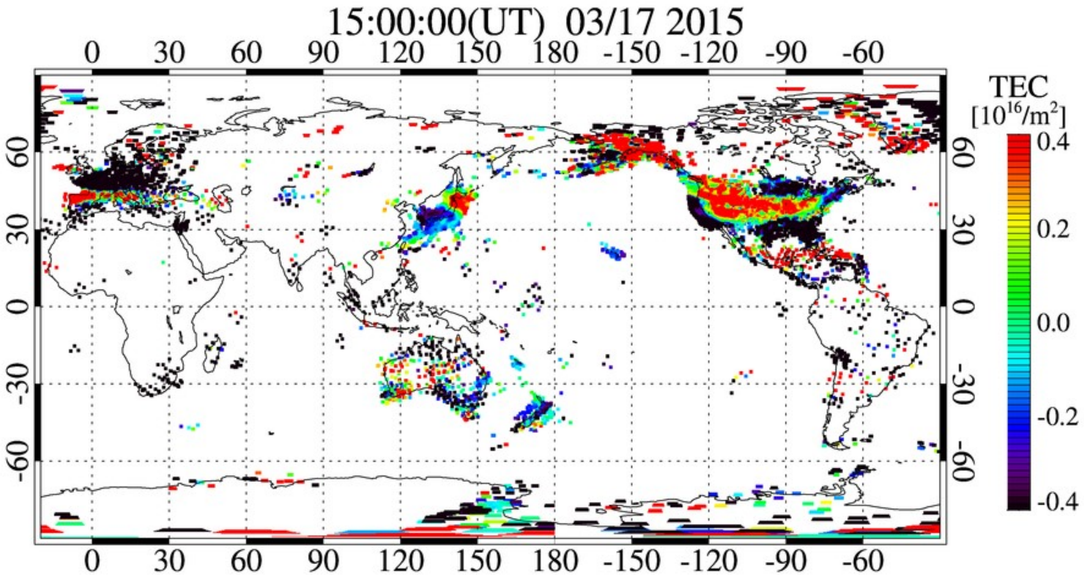
Tsugawa, T., Otsuka, Y., Coster, A. J., and Saito, A. (2007), Medium-scale traveling ionospheric disturbances detected with dense and wide TEC maps over North America, Geophys. Res. Lett., 34, L22101

Europe

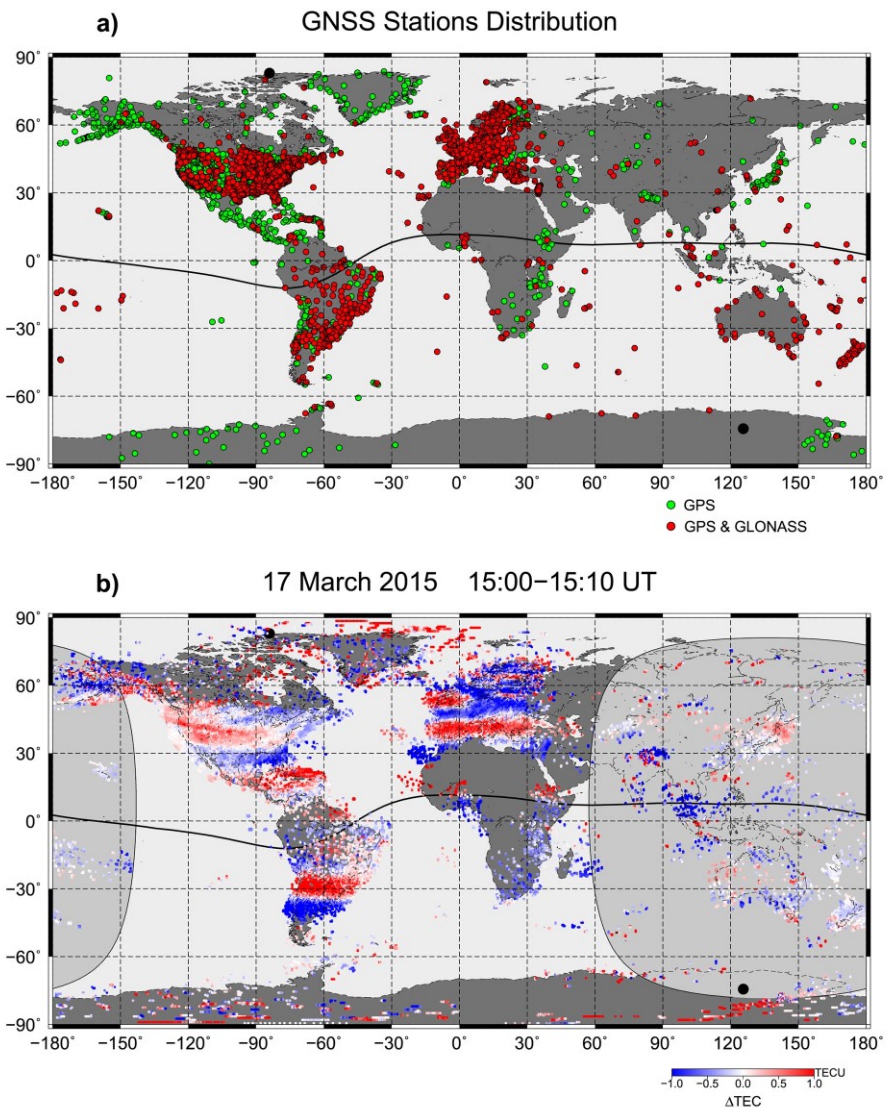


Otsuka, Y., Suzuki, K., Nakagawa, S., Nishioka, M., Shiokawa, K., and Tsugawa, T. (2013), GPS observations of medium-scale traveling ionospheric disturbances over Europe, Ann. Geophys., 31, 163–172

Case Studies: LSTIDs

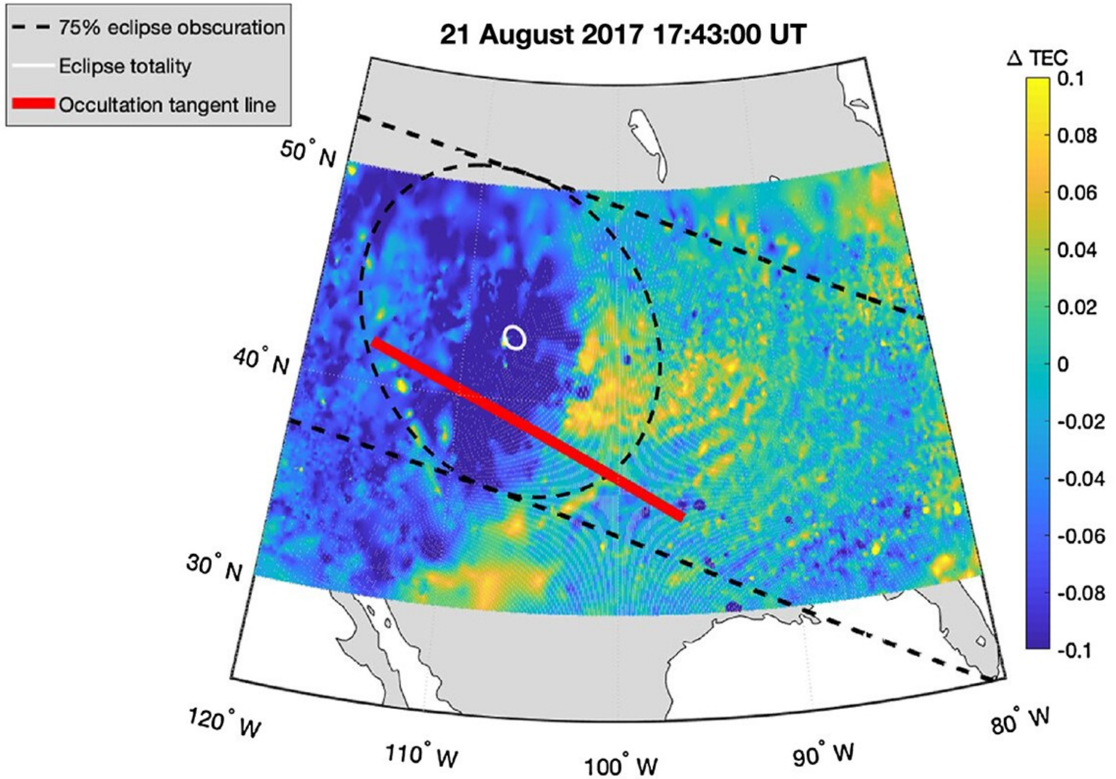


http://seg-web.nict.go.jp/

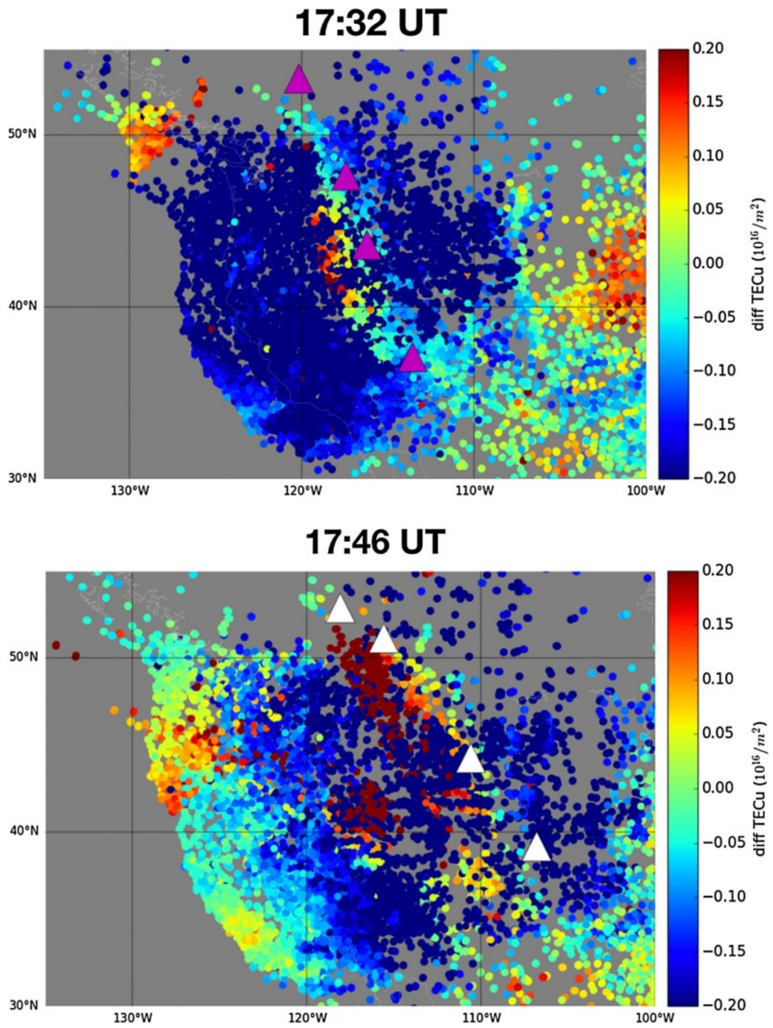


Zakharenkova, I., Astafyeva, E., and Cherniak, I. (2016), GPS and GLONASS observations of large-scale traveling ionospheric disturbances during the 2015 St. Patrick's Day storm, J. Geophys. Res. Space Physics, 121, 12,138– 12,156

Case Studies: Solar Eclipse



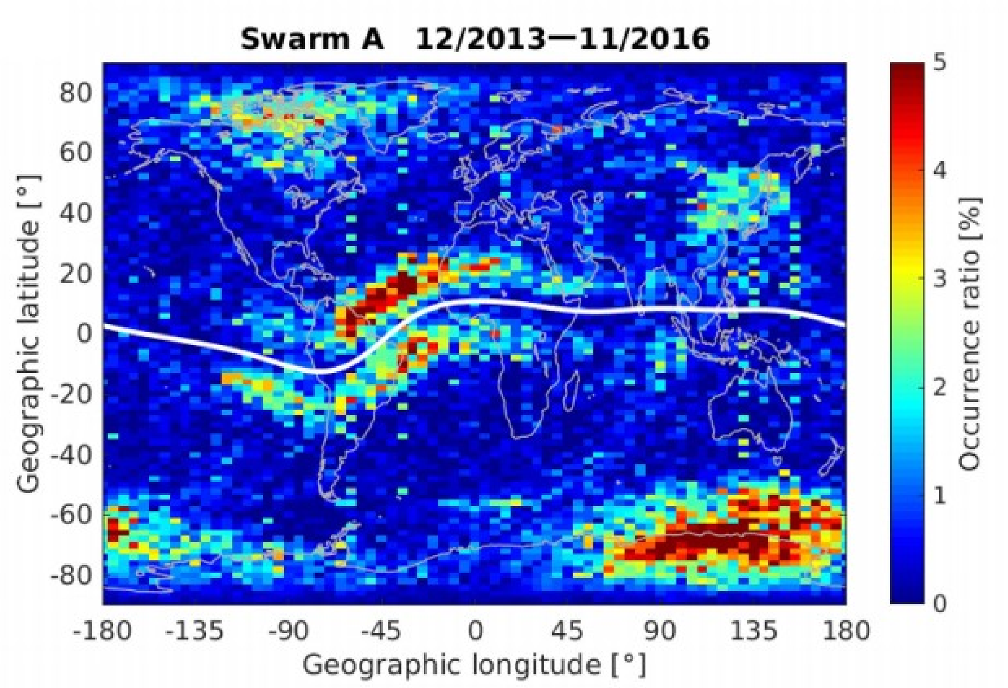
Perry, G. W., Watson, C., Howarth, A. D., Themens, D. R., Foss, V., Langley, R. B., & Yau, A. W. (2019). Topside ionospheric disturbances detected using radio occultation measurements during the August 2017 solar eclipse. Geophysical Research Letters, 46, 7069– 7078



Coster, A. J., Goncharenko, L., Zhang, S.-R., Erickson, P. J., Rideout, W., & Vierinen, J. (2017). GNSS observations of ionospheric variations during the 21 August 2017 solar eclipse. Geophysical Research Letters, 44, 12,041– 12,048

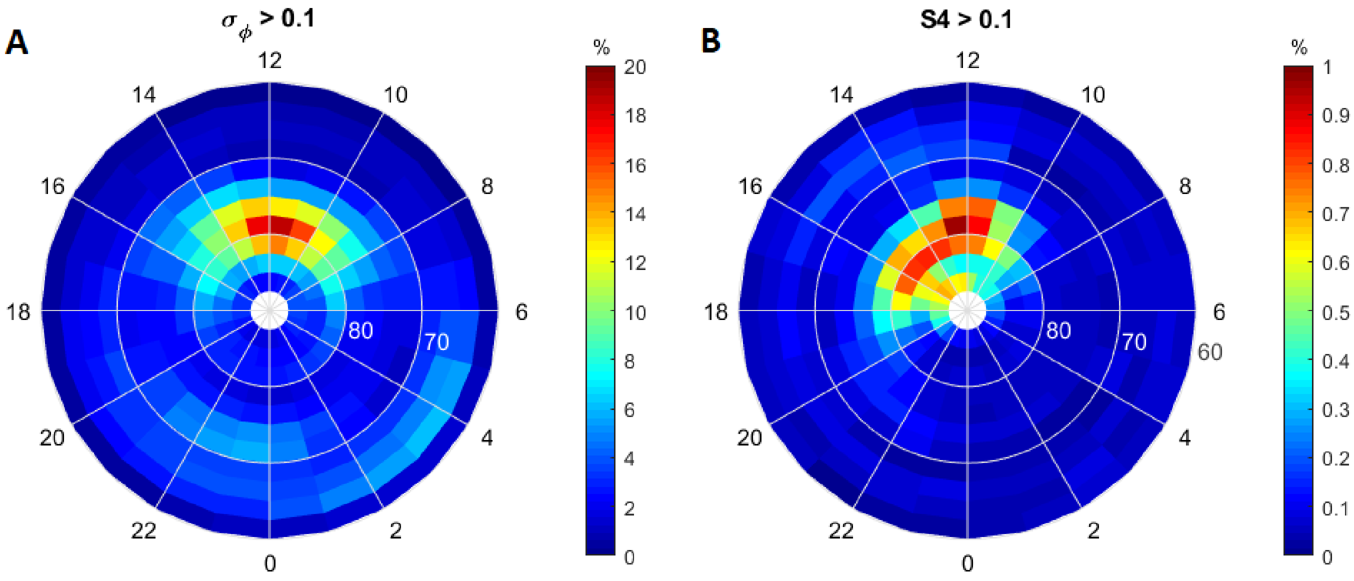
Scintillation studies

Global distribution of GPS signal loss events observed by Swarm A satellite



Xiong, C., Stolle, C., and Park, J. (2018), Climatology of GPS signal loss observed by Swarm satellites, Ann. Geophys., 36, 679–693

Phase fluctuation (A) and amplitude scintillation (B) occurrence rate distribution as a function of MLAT/MLT observed by CHAIN network



Meziane, K., Kashcheyev, A., Patra, S., Jayachandran, P. T., & Hamza, A. M. (2020). Solar cycle variations of GPS amplitude scintillation for the polar region. Space Weather, 18

Market evolution

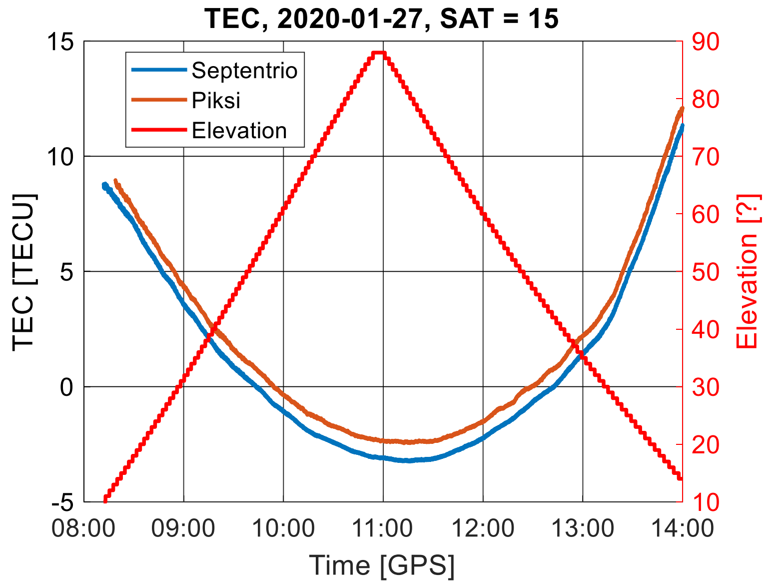
>10k $

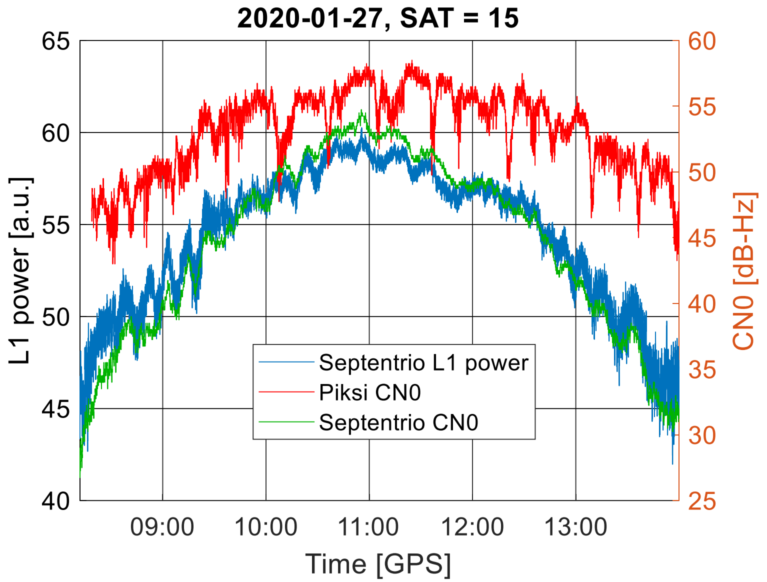
<= 1k $

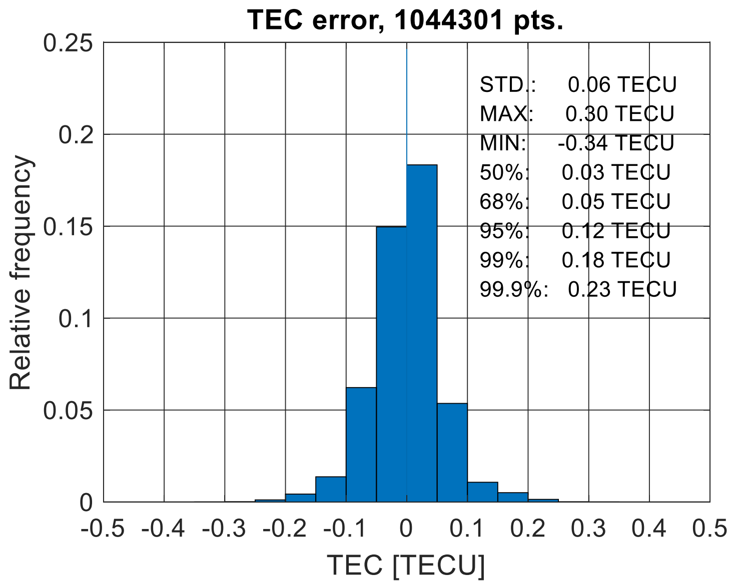
GNSS receivers under test

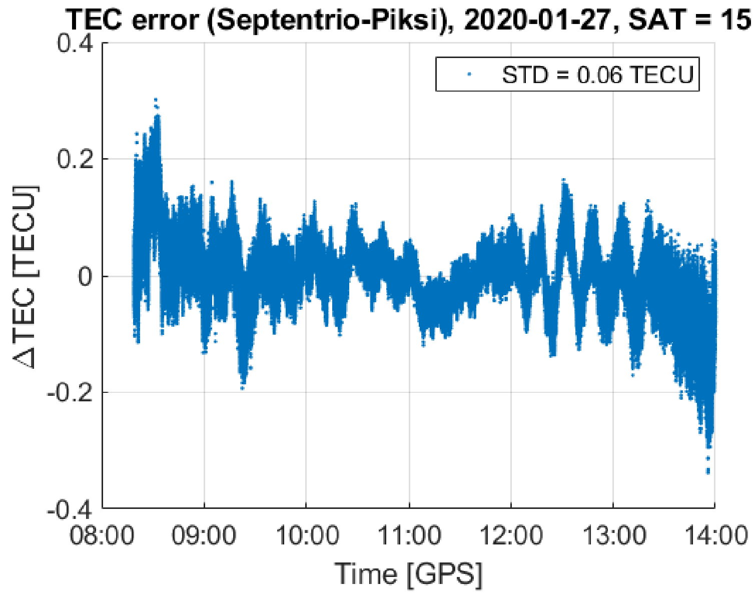
- Septentrio PolaRxS Pro & PolaNt*_GG antenna, 50 Hz, >10k $
- Swift Piksi Multi, 20 Hz, 1k $
- Tersus BX-316D, 20 Hz, 1k $
- U-Blox ZED-F9P, 20 Hz , 250 $

Piksi (PolaNt*_GG) vs **Septentrio** (GPS-702-GG), on **UNB roof**

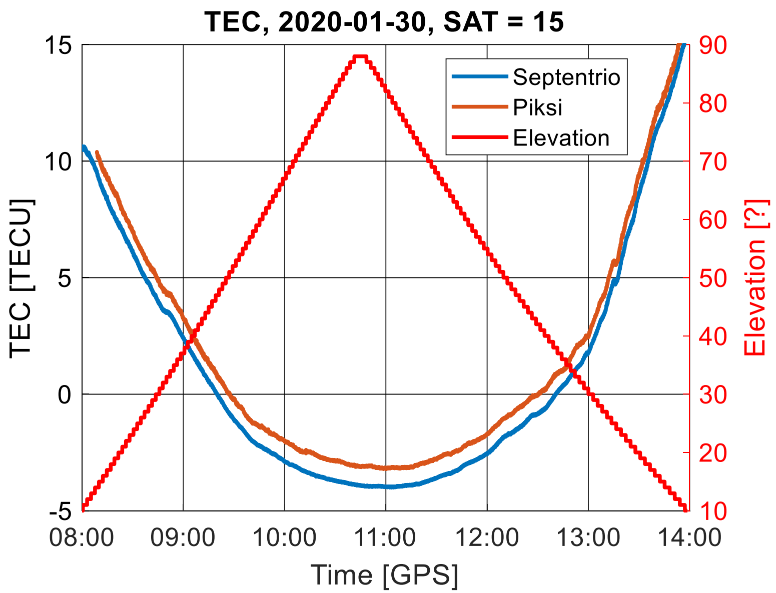


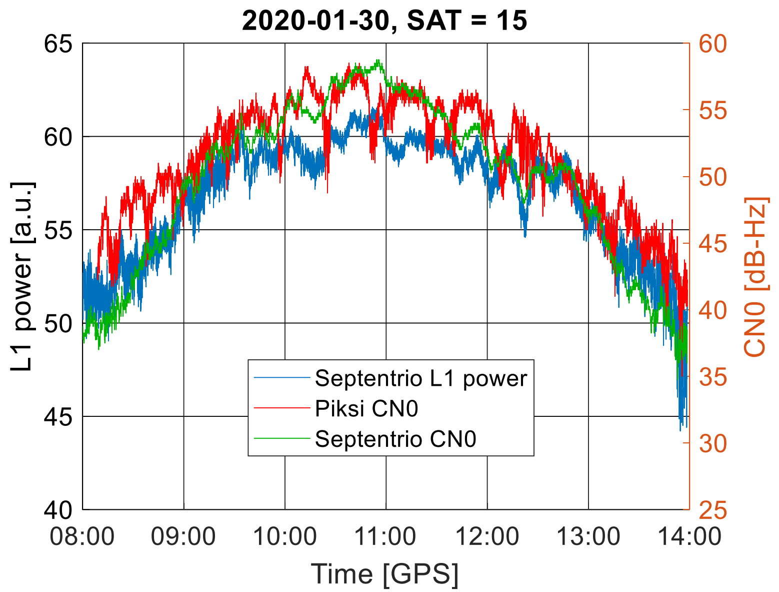


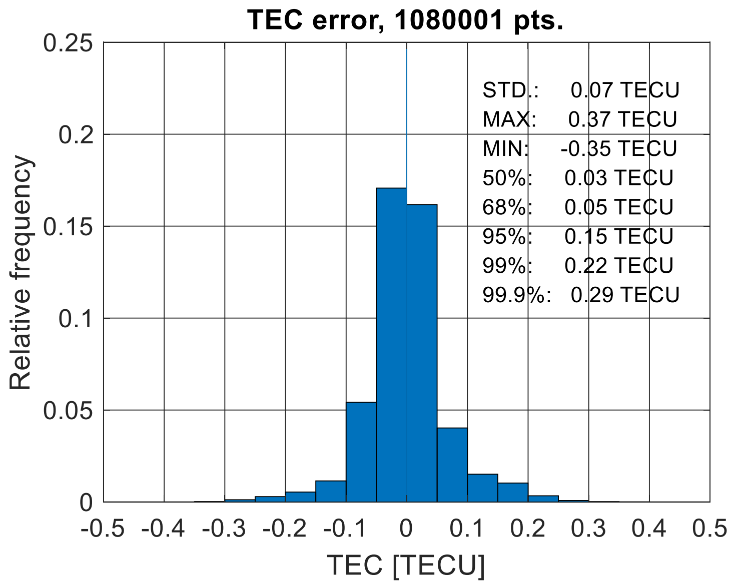


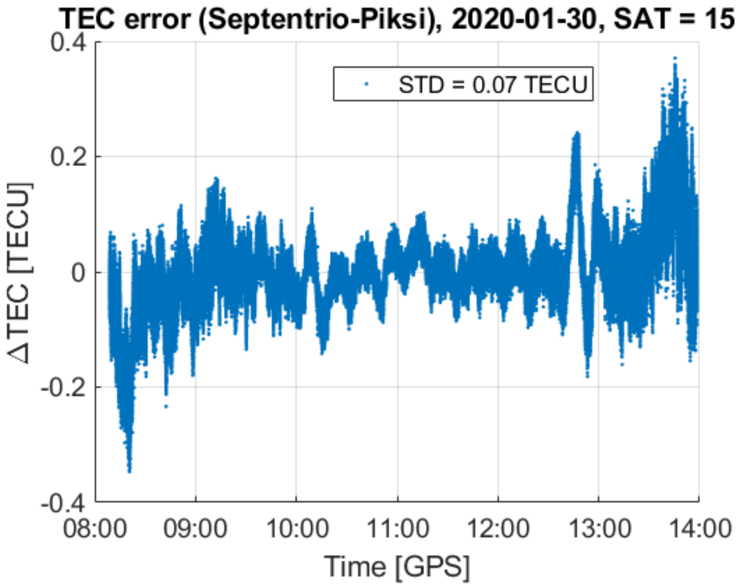


Piksi (GPS-702-GG) vs **Septentrio** (PolaNt*_GG), on **UNB roof**

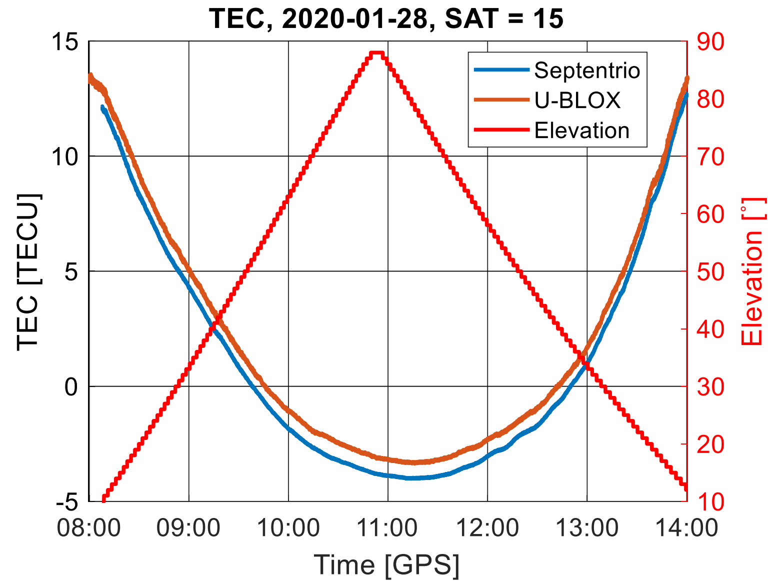

TEC, 2020-01-30, SAT = 15

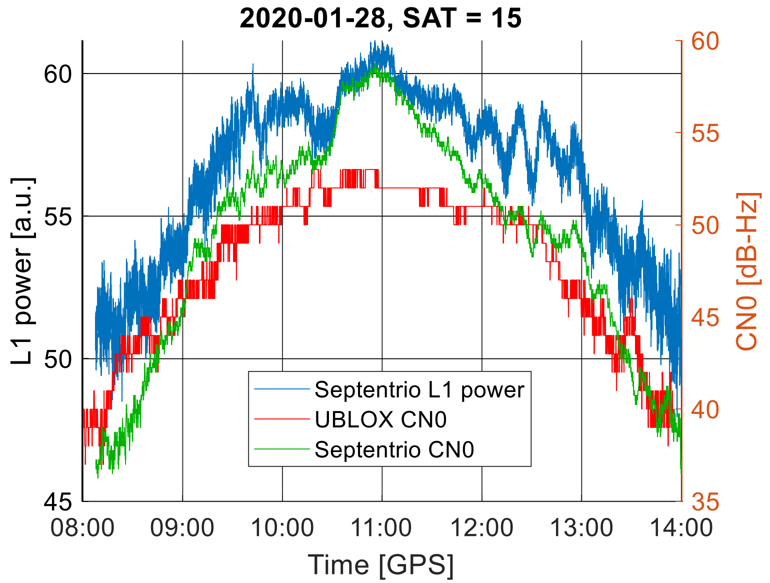

2020-01-30, SAT = 15

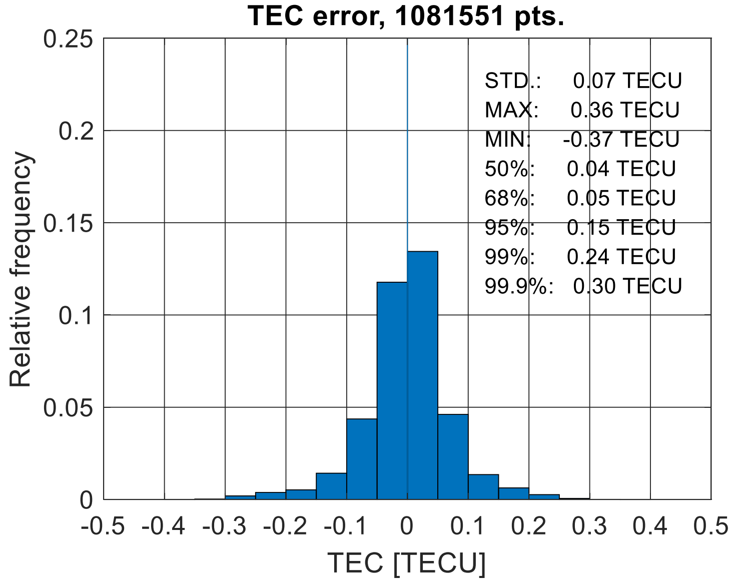

TEC error, 1080001 pts.

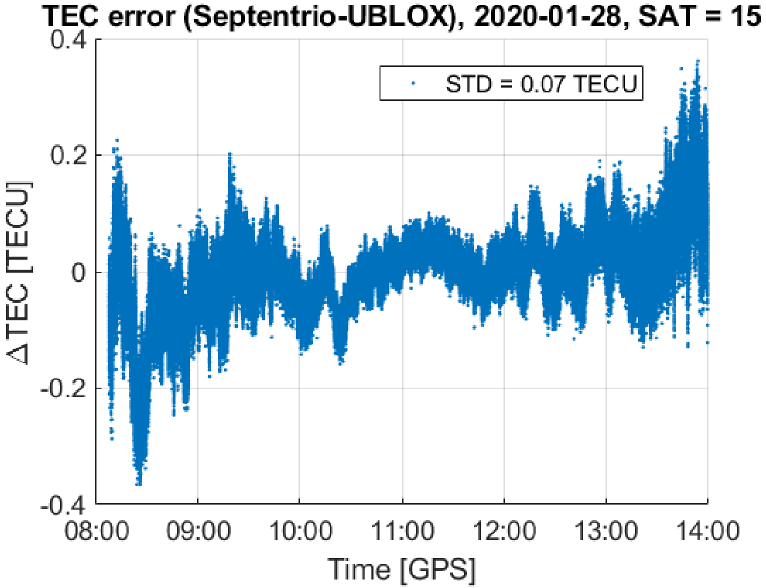

TEC error (Septentrio-Piksi), 2020-01-30, SAT = 15

U-Blox (GPS-702-GG) vs **Septentrio** (PolaNt*_GG), on **UNB roof**

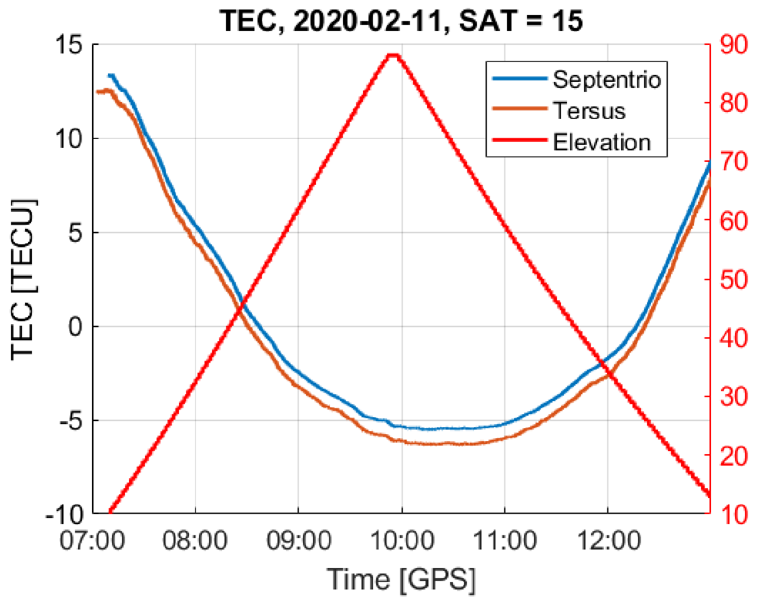

TEC, 2020-01-28, SAT = 15

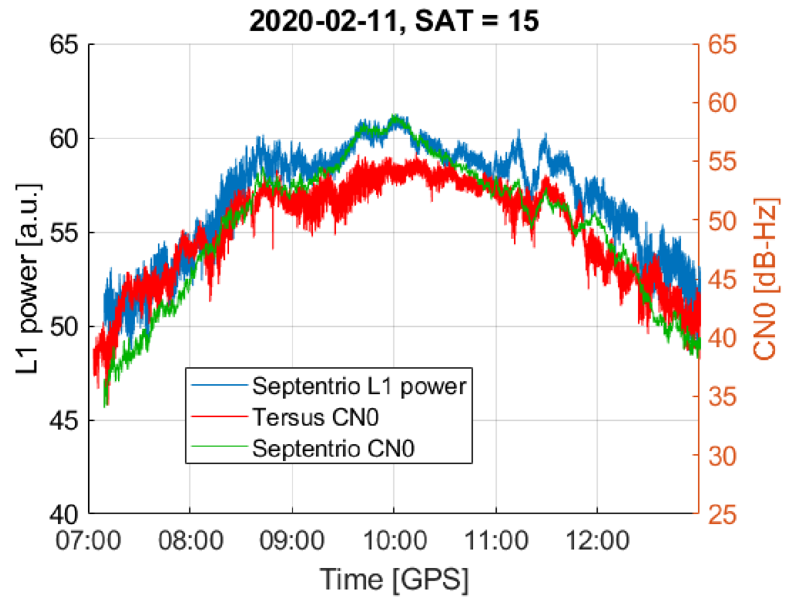

2020-01-28, SAT = 15

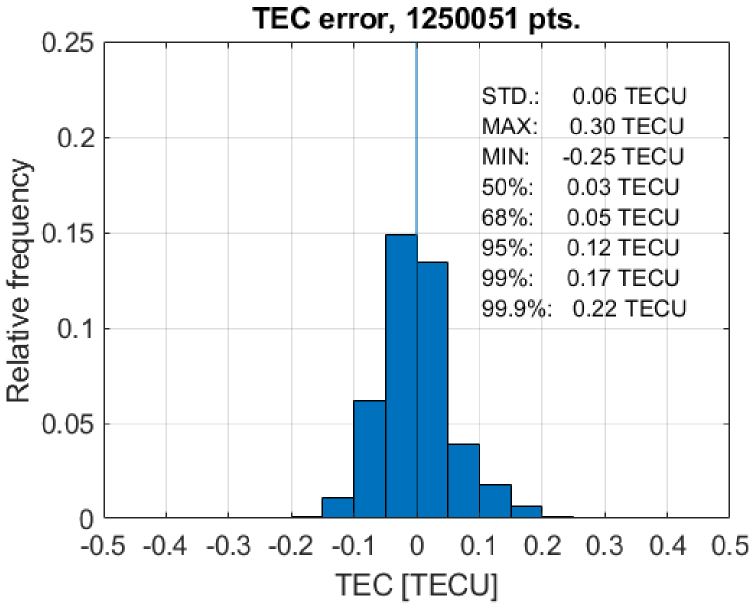

TEC error, 1081551 pts.


TEC error (Septentrio-UBLOX), 2020-01-28, SAT = 15

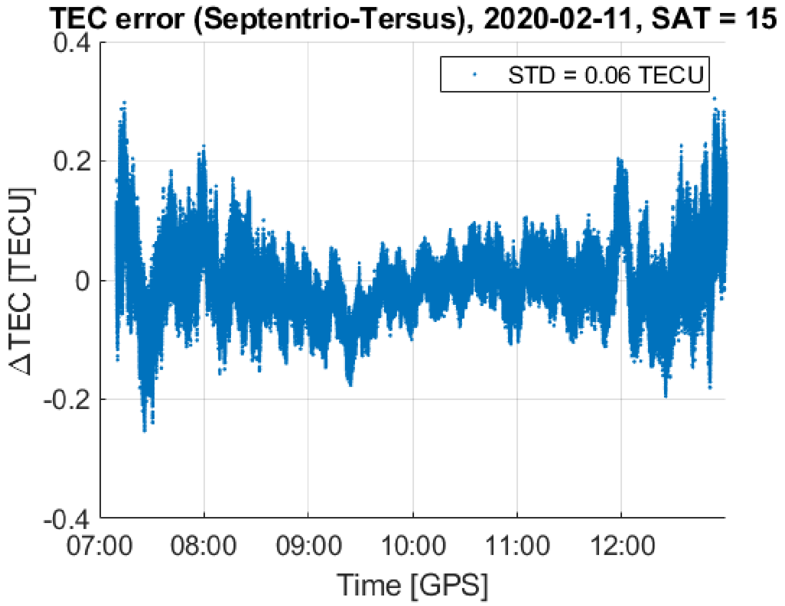
Tersus (GPS-702-GG) vs **Septentrio** (PolaNt*_GG), on **UNB roof**







STD.: 0.06 TECU
MAX: 0.30 TECU
MIN: -0.25 TECU
50%: 0.03 TECU
68%: 0.05 TECU
95%: 0.12 TECU
99%: 0.17 TECU
99.9%: 0.22 TECU



Conclusions

- Low-cost equipment CAN be used to obtain information about the state of the ionosphere. It might be considered an alternative or a complement to existing conventional instruments

- Long-term simultaneous measurements of an SDR-based ionospheric sounder and a conventional high-power ionosonde have shown a good correspondence of the obtained data

- Low-cost dual frequency GNSS receivers can be a good alternative to estimate TEC values

- More testing must be done in order to understand whether they can be used for scintillation monitoring