Total square-Root Electron Content (TREC): Sounding the Ionosphere with ELF Whistlers Detected by the Swarm Mission

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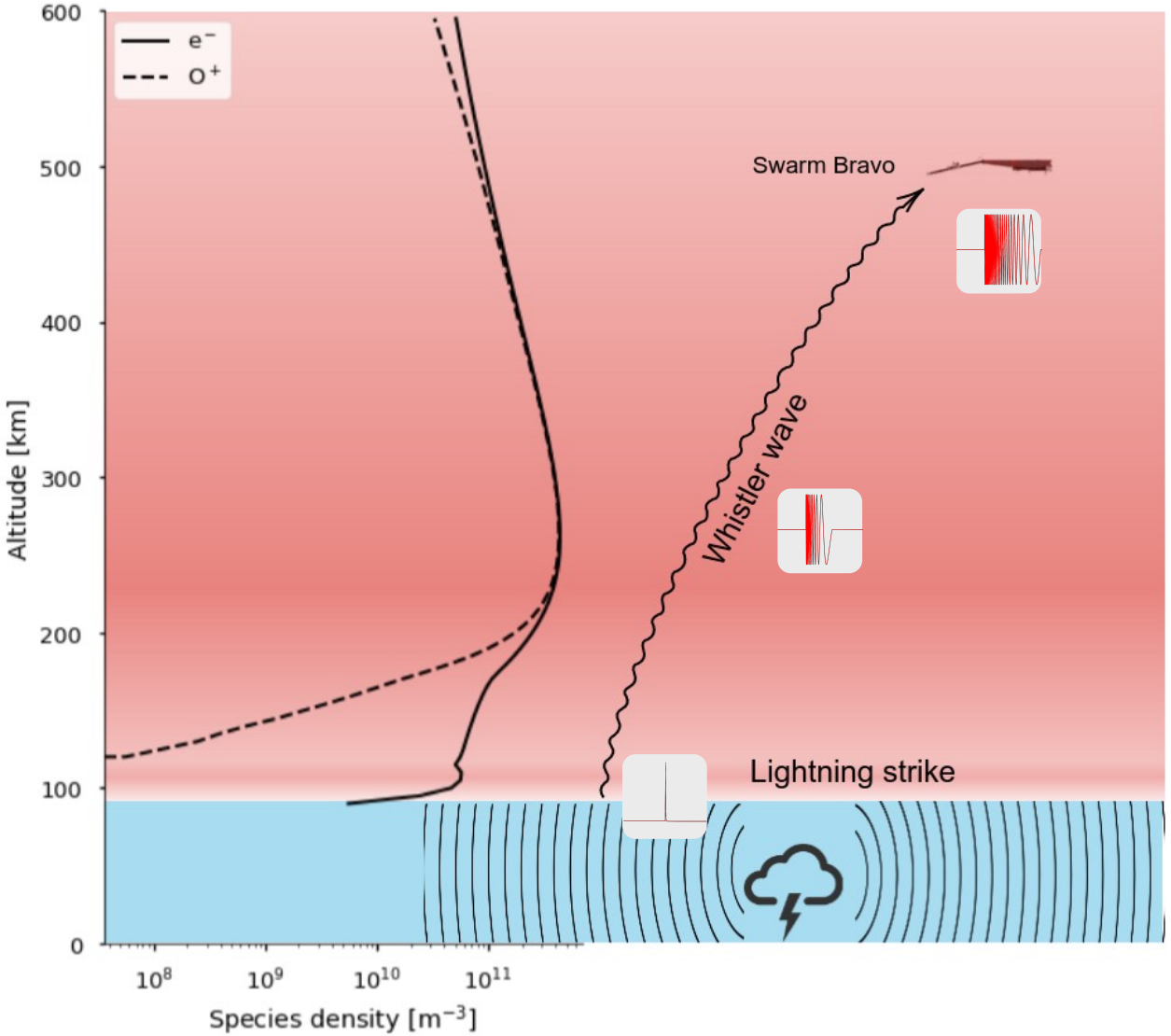
Whistler in Extremely Low Frequency: what is this ?



- Whistlers in Extremely Low Frequency (ELF): **Electromagnetic** signals propagating through the **ionosphere**
- Originate from **lightning** generated impulsion **leaking** into the ionosphere
- Detected by Swarm **Absolute Scalar Magnetometers** (ASM) during **burst sessions**
- Whistlers are **dispersed** during their propagation depending on the **ionospheric condition**
- The propagation **“follows” the magnetic field**, i.e. ψ is mostly constant

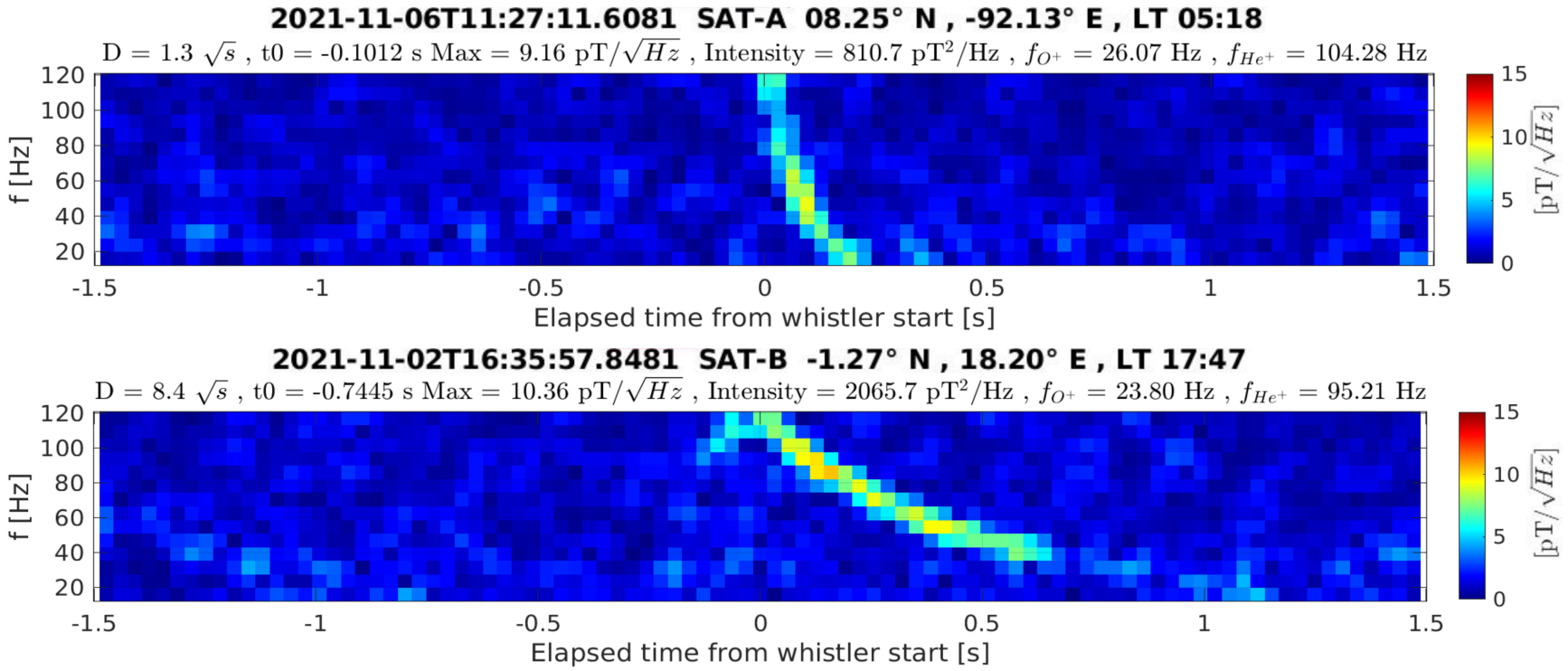
$$\psi = \angle(\vec{k}, \vec{B})$$

Lightning Generated Whistlers detected by Swarm

The whistlers data come from the **burst mode sessions** of the **ASM** (one week every month for Alpha and Bravo):

- **WHIxEVT_2_ product**: 100000+ detections, up to several hundreds a day
- Whistlers detection between **10 Hz** and **120 Hz:** ELF range

[See poster of Pierdavide Coïsson]



Objective:

Retrieve ionospheric parameters from Swarm's whistler data

ELF ionospheric propagation theory

- Neutral, cold, collisionless, 1D plasma containing only e^- and O^+
- For ELF propagation above the gyrofrequency f_{gi} of the plasma

Stix [1966] equation for the refractive index:

$$n^2 = \frac{RL\sin^2\psi + PS(1+\cos^2\psi) \pm \sqrt{(RL-PS)^2\sin^4\psi + 4P^2D^2\cos^2\psi}}{2S\sin^2\psi + 2P\cos^2\psi}$$

R, L, P, S, D depend on the plasma and the magnetic field

In **ELF**, within the **ionosphere**, we have the following: $f_{pe} \gg f \;;\; f_{ge} \gg f \;;\; f_{pi} \gg f \;;\; m_i \gg m_e$

$$n^2 \simeq \frac{f_{pi}^2}{f_{gi}^2 - f^2}\left(1 + \frac{1}{2}\tan^2\psi - \sqrt{\frac{1}{4}\tan^4\psi + \frac{f^2}{f_{gi}^2\cos^2\psi}}\right)$$

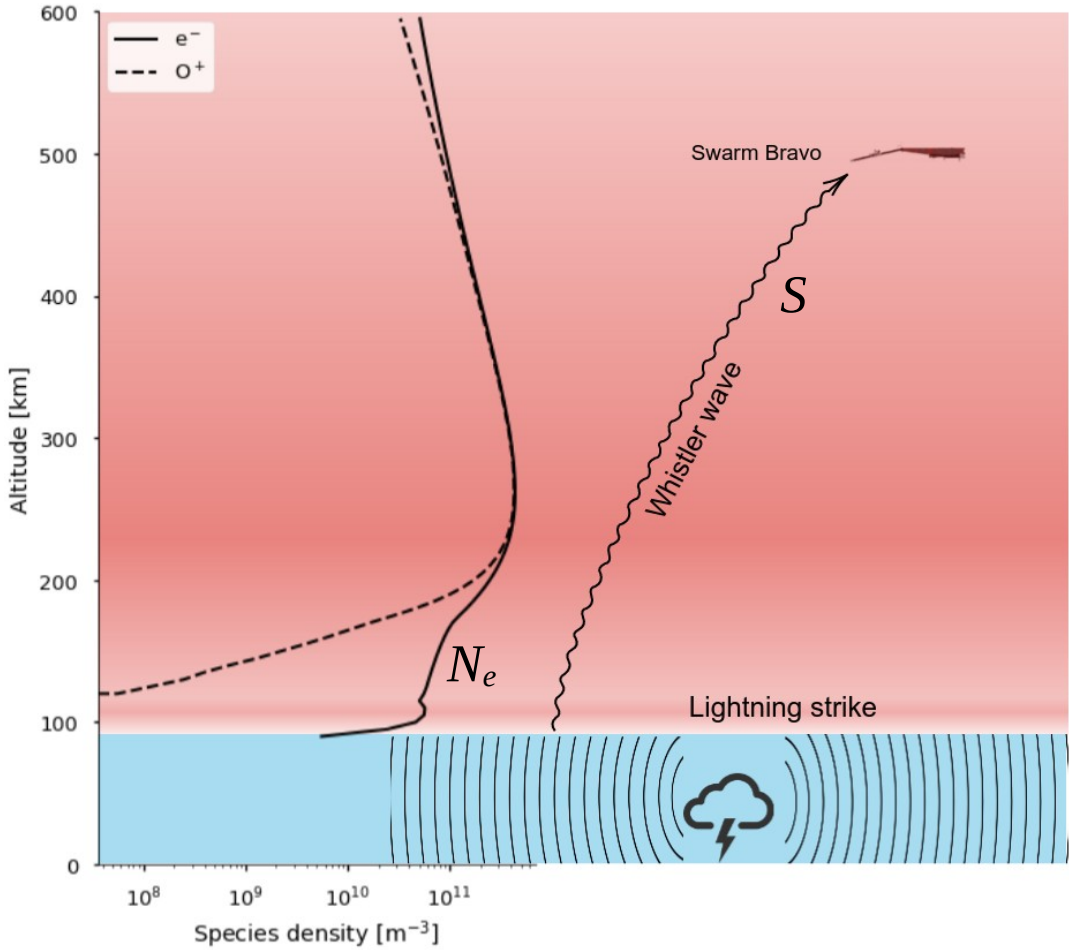
Link between the group delay and the electron density

$$T(f) \simeq K(f, B, \psi) \int_S \sqrt{N_e(s)}\, ds$$

- T is the **group delay** for the signal to propagate through the ionosphere to our instrument.
- N_e is the **electron density**
- S is the **ray path length**
- K is a coefficient that depends on the **frequency** f, the strength of the **magnetic field** B, and ψ

We call this integral **Total Root Electron Content** (TREC)

$$TREC(S) = \int_S \sqrt{N_e(s)}\, ds$$



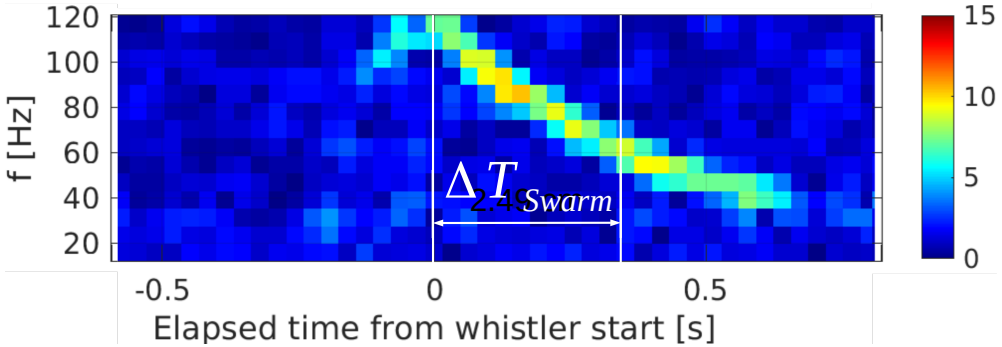
Dual frequency method

How do we derive the TREC from Swarm's whistler signal ?

$$T(f_i) \simeq K_i \; TREC(S_i)$$

We define the mean path S and σ:

$$S(r) = \frac{S_2(r)+S_1(r)}{2} \qquad \sigma(r) = \frac{S_2(r)-S_1(r)}{2}$$



At frequencies f_1 and f_2 for the **mean ray path S** :

$$\underbrace{T(f_2)-T(f_1)}_{\Delta T} = \Delta T(f_1,f_2) = \gamma_{12} \; TREC(S) + b_{12}$$

where γ_{12} and b_{12} are functions of K_1 and K_2 and σ

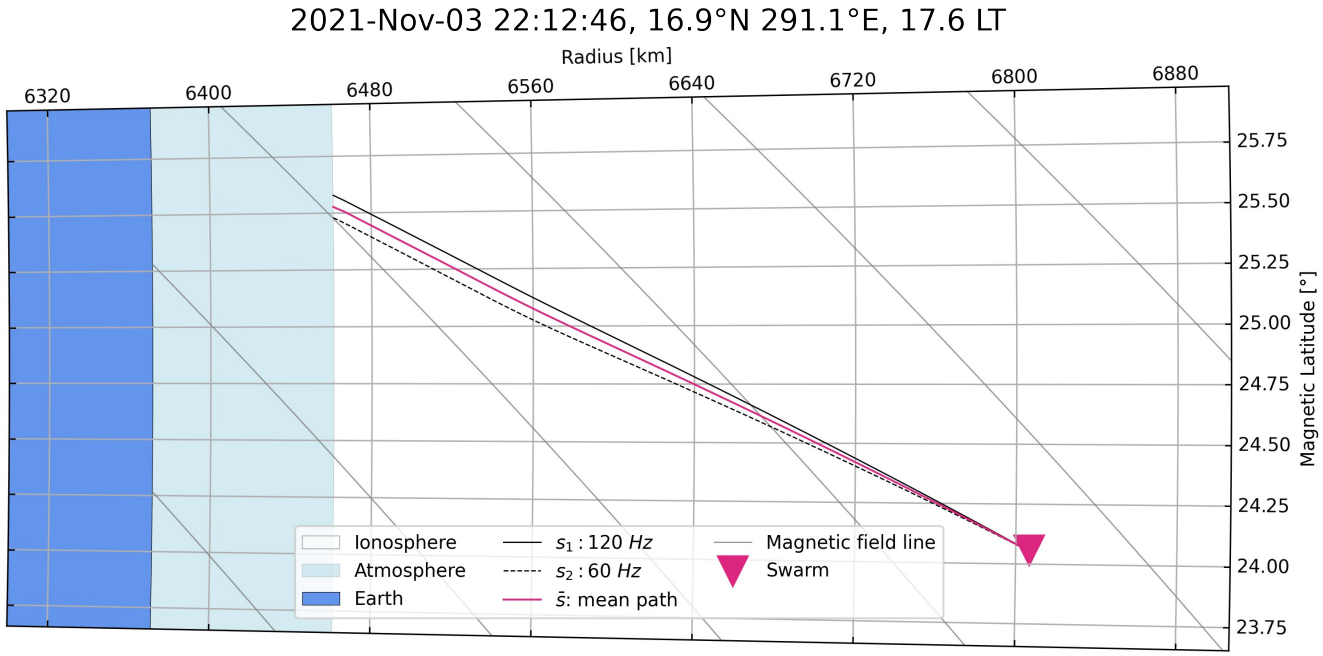
If we know the **parameters γ_{12} and b_{12}** we can estimate the **TREC** from the **observed ΔT**.

$$TREC(S) = \frac{\Delta T(f_1,f_2) - b_{12}}{\gamma_{12}}$$

Propagation modelisation with ray-tracing

Initial wave-vector is vertical at the base of the ionosphere (90 km)

- **Climatological IRI** (2016 or 2020) [Bilitza et al. 2017 and 2022]
- Magnetic field: **IGRF-13** [Alken et al. 2021]
- Outputs for each frequency:
  - **group delay T_1 and T_2**
  - **ray path S_1 and S_2**



Estimation of the **coefficients γ_{12} and b_{12}** with ray tracing through IRI:

$$\gamma_{12} = K_2 - K_1 = \frac{T_2}{TREC(S_2)} - \frac{T_1}{TREC(S_1)} \qquad b_{12} = (K_2 + K_1) \int_{r_0}^{r_{sw}} \sqrt{N_e(r)} \frac{d\sigma}{dr} dr$$

Dual frequency method

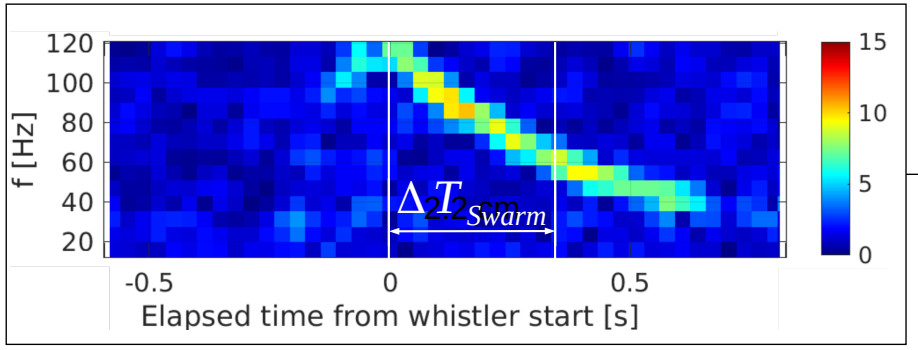
Models

Climatological IRI

- TREC from direct integration
- T_1 and T_2 from ray-tracing

γ_{12} b_{12} S_{IRI}

ASM detections



ΔT_{Swarm}

$TREC_{Swarm}(S_{IRI})$

Validation method

Models

Climatological IRI

- TREC from direct integration
- T_1 and T_2 from ray-tracing

Independant observations

Ionosonde + Swarm's Langmuir Probe (LP)

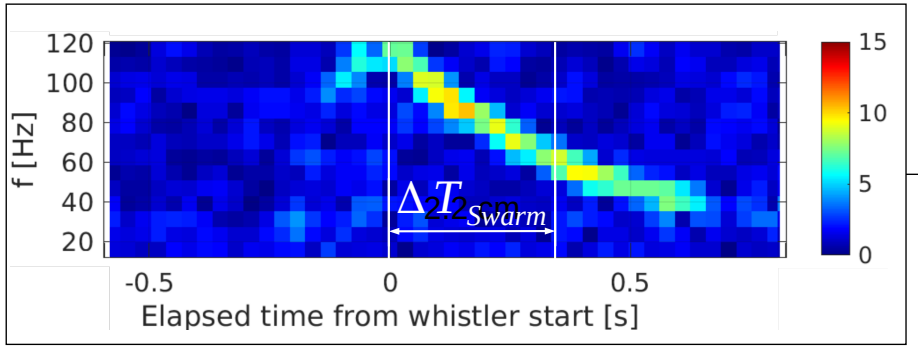
Millstone Hill, Ramey, Boa Vista, Santa Maria, Grahamstown

γ_{12} b_{12} S_{IRI}

$TREC_{IONO+LP}(S_{IRI})$

$TREC_{IRI}(S_{IRI})$

ASM detections



ΔT_{Swarm}

$TREC_{Swarm}(S_{IRI})$

Verification data: Ionosonde and Langmuir probes

- Chosen stations: Millstone Hill, Ramey, Boa-Vista and Santa Maria, Grahamstown
- Selection of whistlers occurring **within 500 km** of an active ionosonde station
- Keep whistlers **within 7.5 minutes of the closest profiles**

Topside (above hmF2) of ionograms are usually modelled. We replace it with a better informed topside:

- Modeled with the **NeQuick2 topside function**
- Anchored on Swarm **Langmuir Probe** (LP) plasma density

Results (Boa-Vista, near equator) and discussion

$TREC_{Swarm}(S_{IRI})$

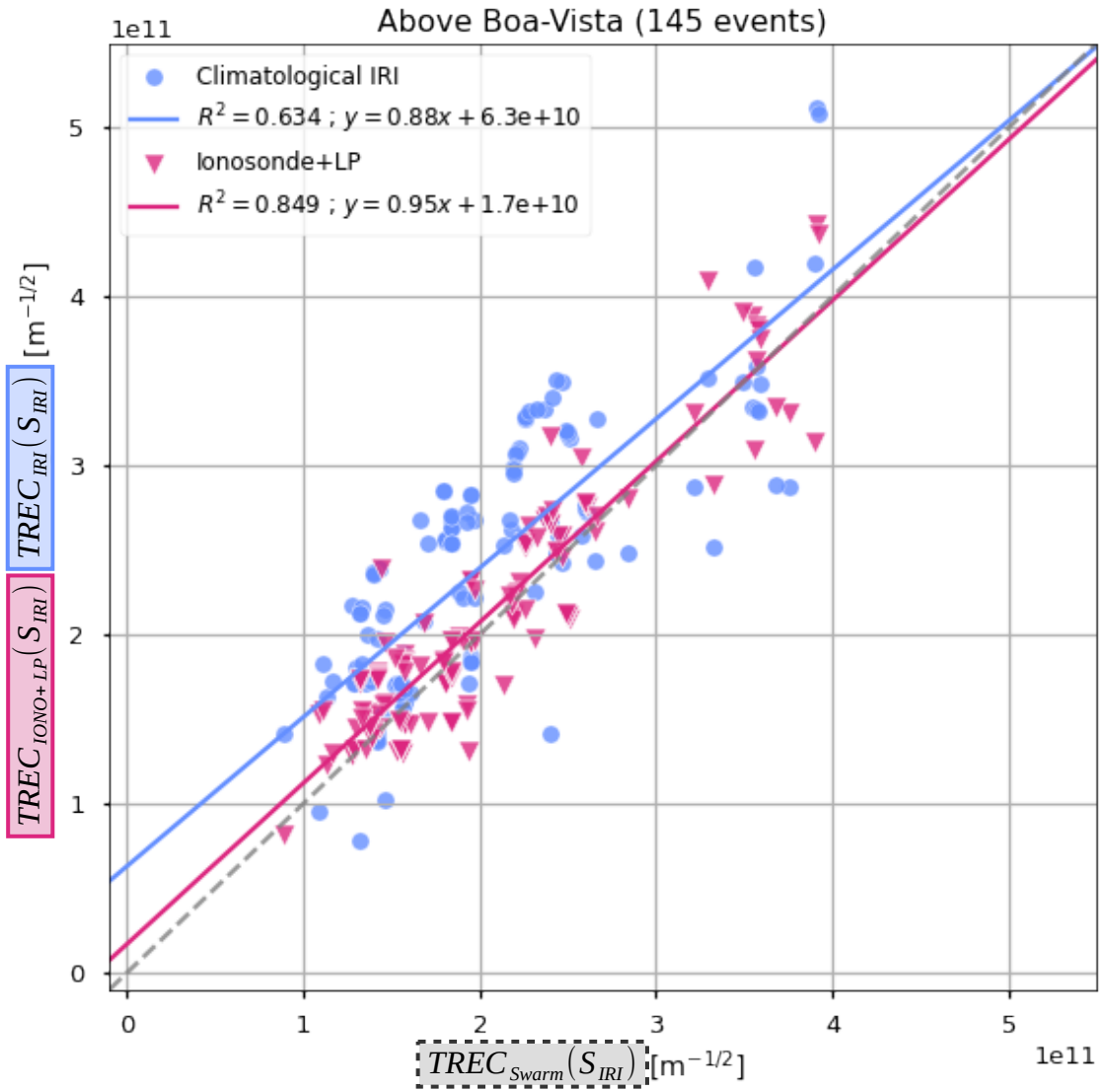
Horizontal axis: Calculation of the TREC using
- ΔT from Swarm's data
- γ **and** b **coefficient** from the ray-tracing

$TREC_{IRI}(S_{IRI})$

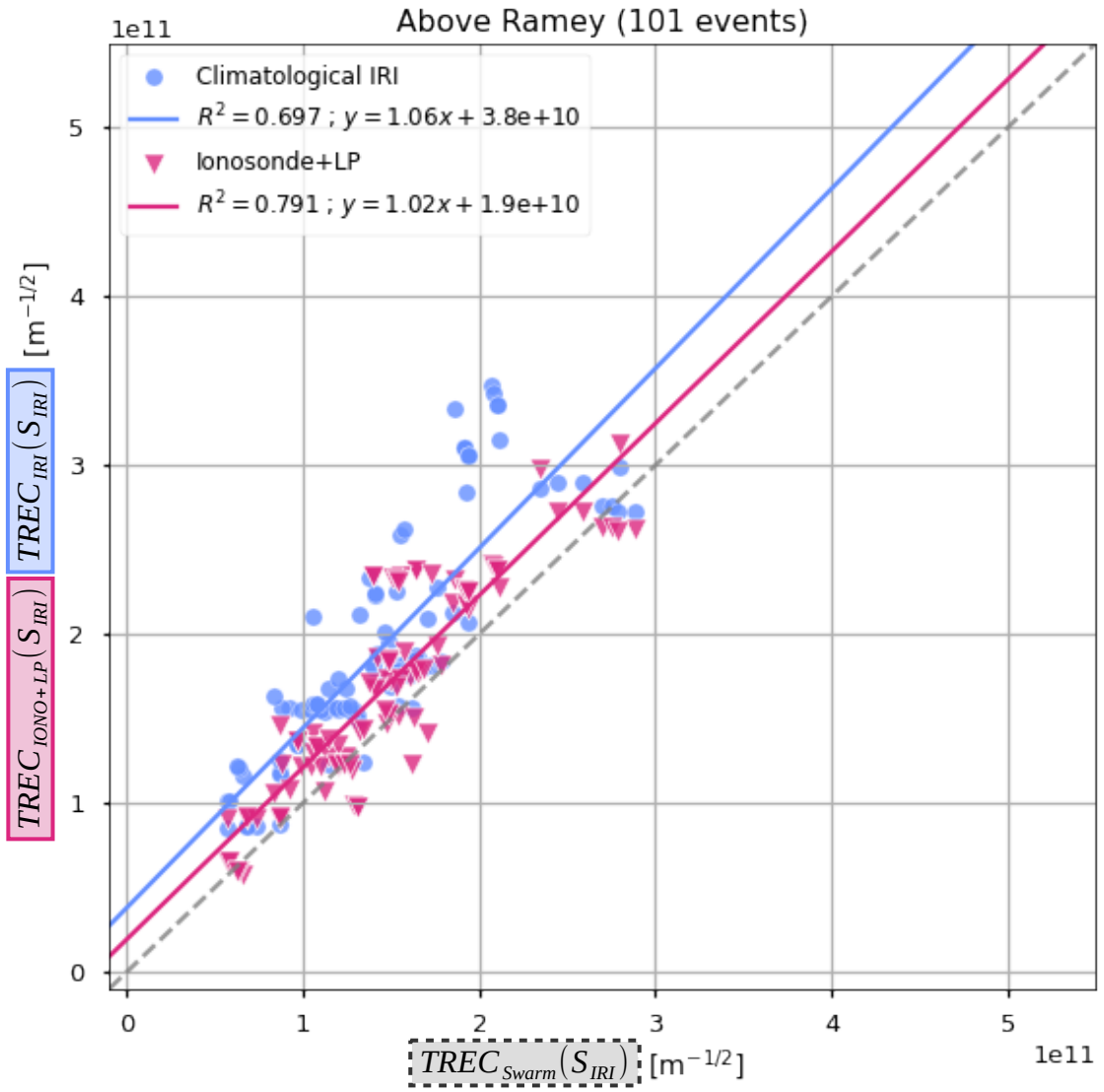
Vertical axis: Direct integration of the **climatological IRI profile** along the climatological IRI ray-path
→ **climatological value**

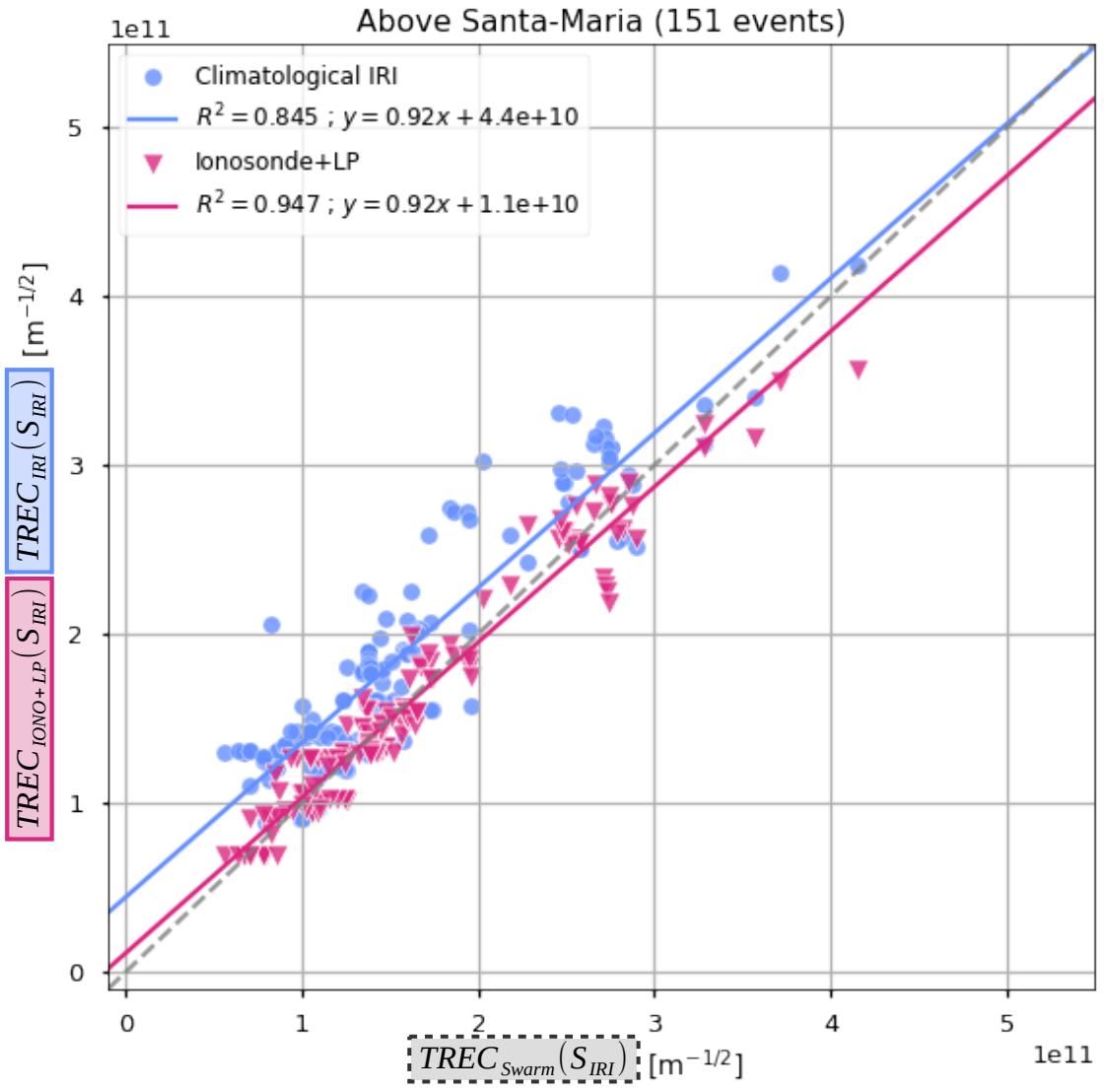
$TREC_{IONO+LP}(S_{IRI})$

Vertical axis: Direct integration of the **Ionosonde profile corrected by the LP value** along the same climatological IRI ray-path
→ **Ionosonde and LP observations**

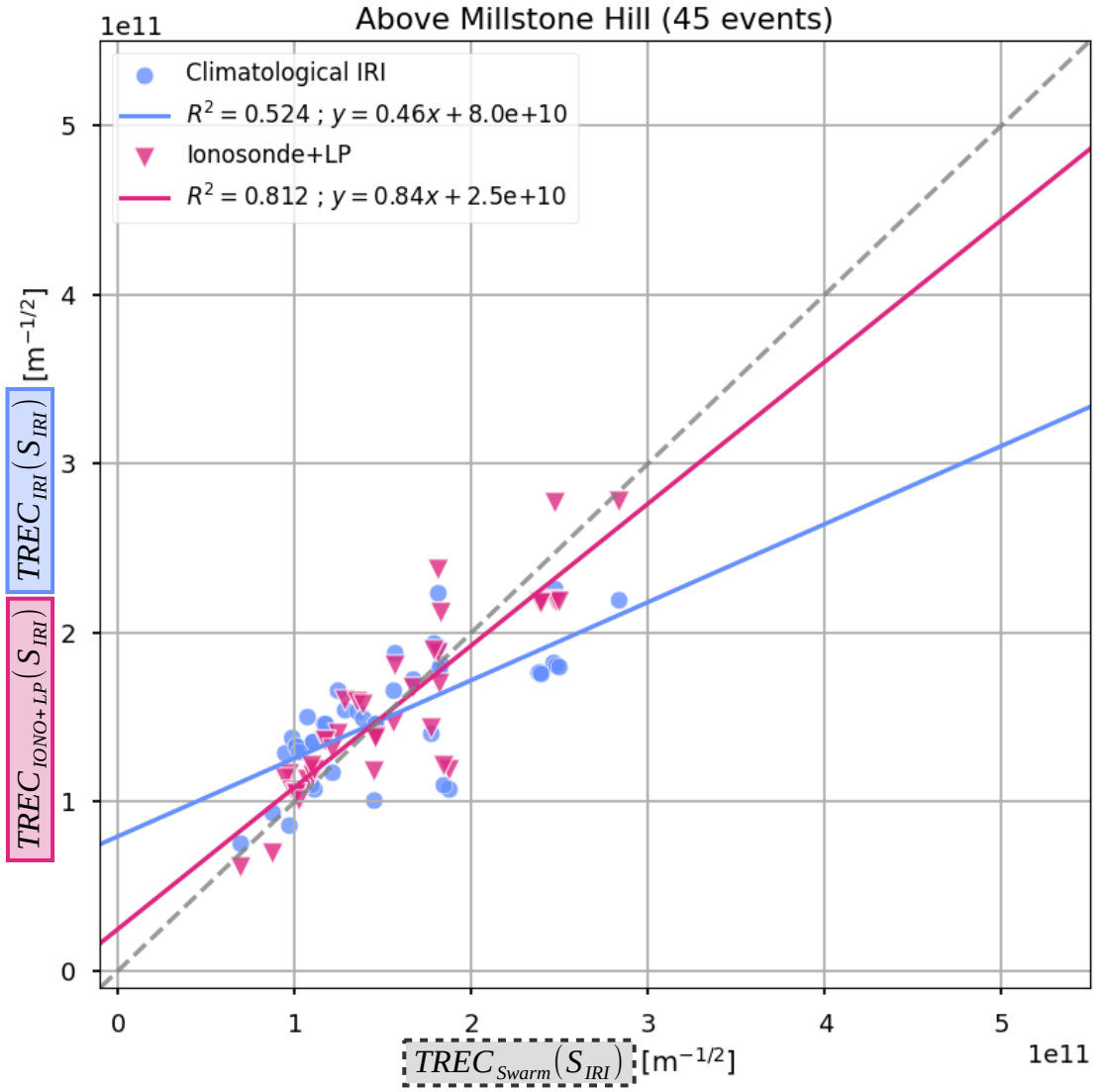


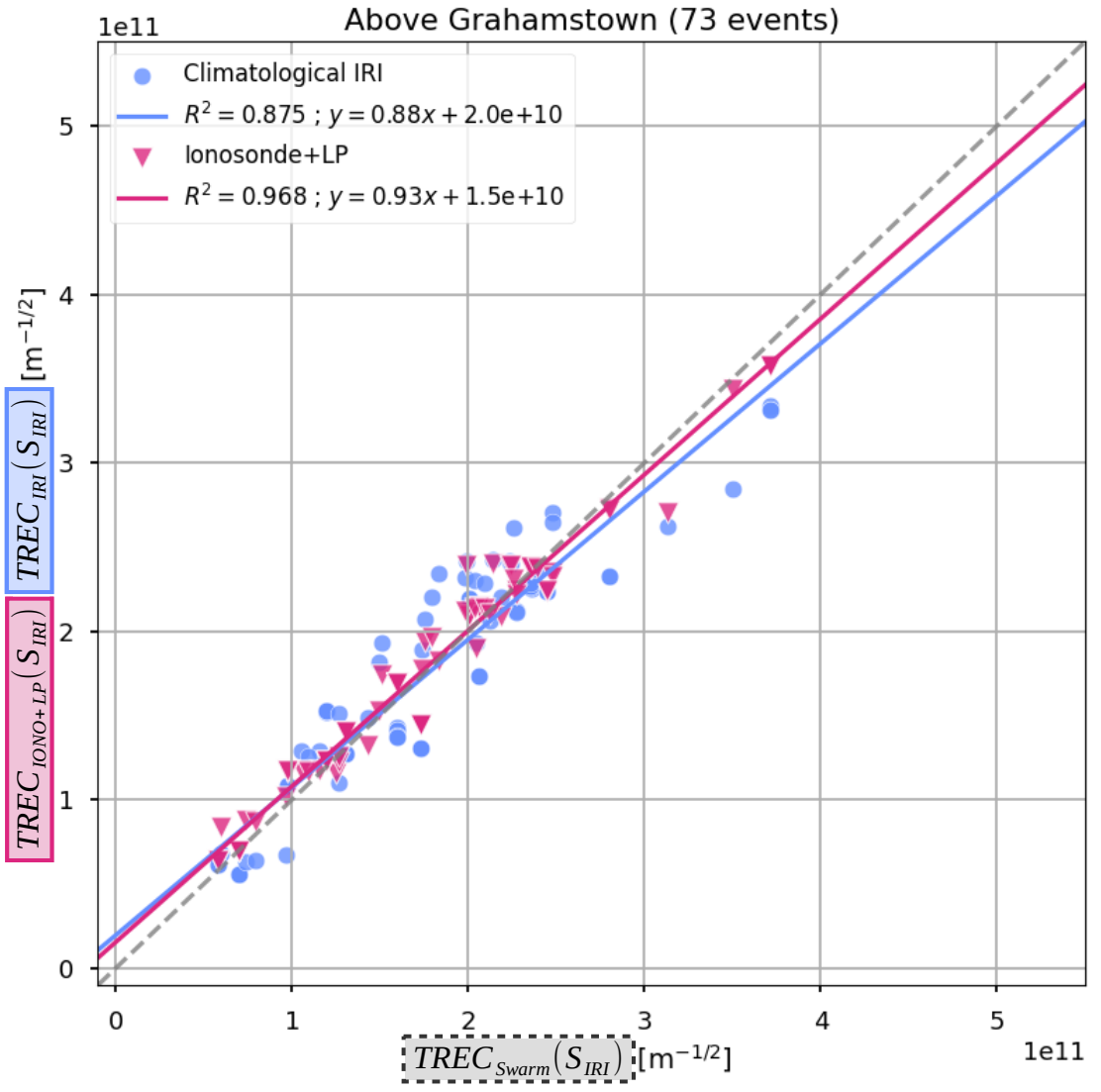
Ramey and Santa-Maria (low-latitude)





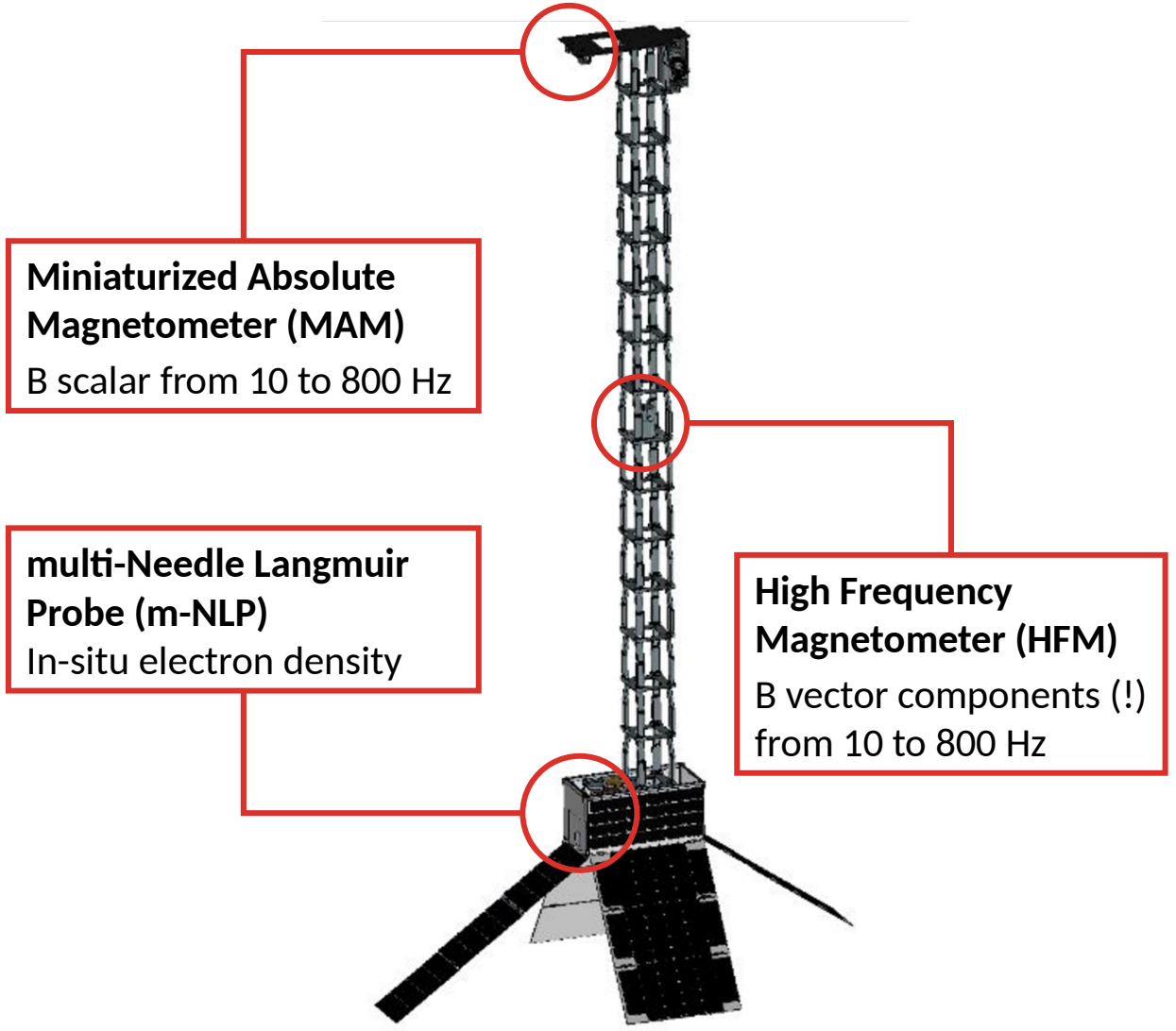
Millstone Hill and Grahamstown (mid-latitude)





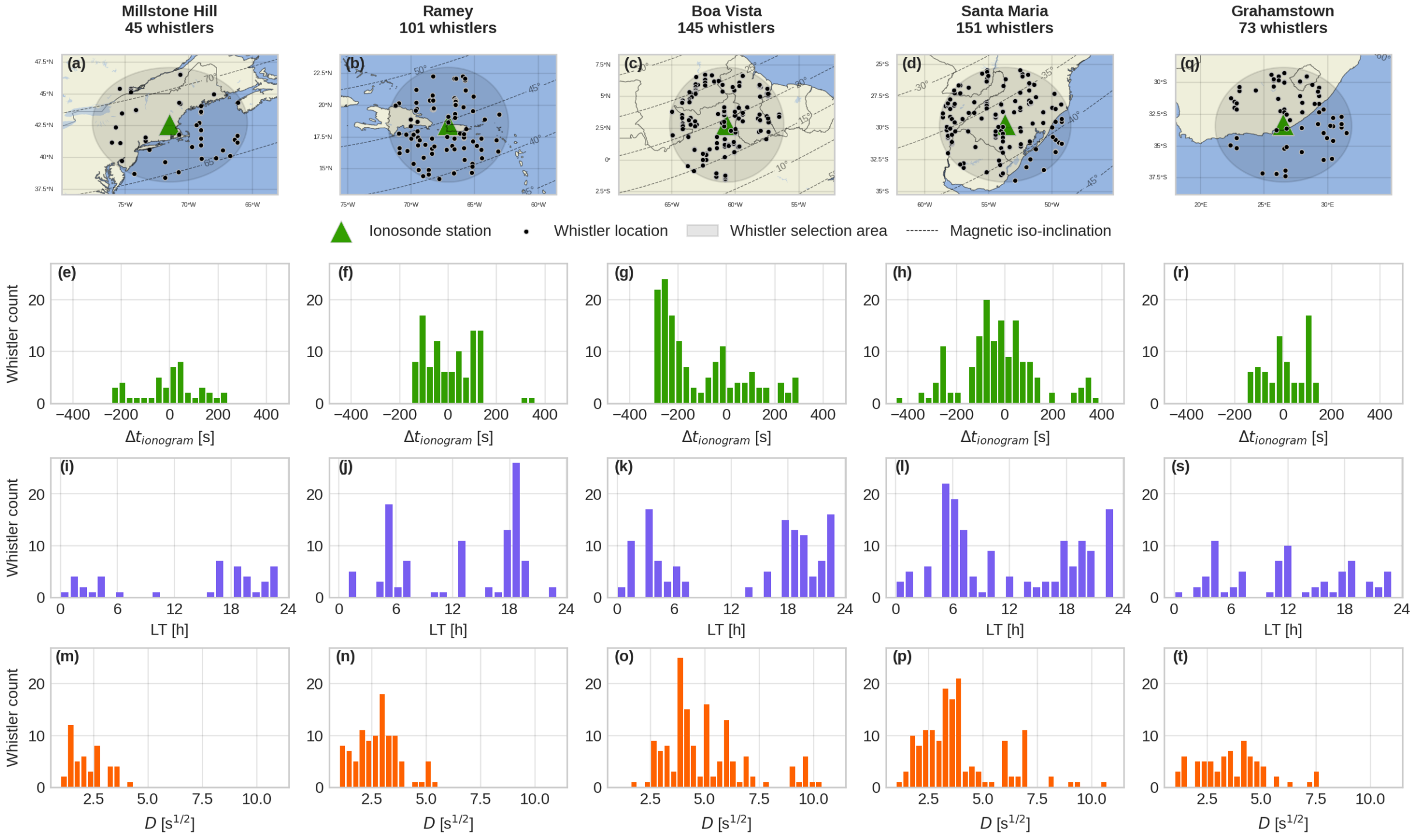
Conclusions and perspectives

- The TREC is a new, valuable, measurement of the **ionization** state of the ionosphere
- Can be recovered from **ELF whistler** detection by Swarm
- Can be replicated on other missions e.g.:
  - **CSES** [poster of Qiao Wang]**,**
  - **DEMETER,**
  - **NanoMagSat** (up to 800 Hz)



More informations: jenner@ipgp.fr

Thank you


Millstone Hill
45 whistlers
Ramey
101 whistlers
Boa Vista
145 whistlers
Santa Maria
151 whistlers
Grahamstown
73 whistlers
(a)
(b)
(c)
(d)
(q)
Ionosonde station
Whistler location
Whistler selection area
Magnetic iso-inclination
(e)
(f)
(g)
(h)
(r)
(i)
(j)
(k)
(l)
(s)
(m)
(n)
(o)
(p)
(t)
Whistler count
$\Delta t_{ionogram}$ [s]
LT [h]
D [s$^{1/2}$]