RÉPUBLIQUE FRANÇAISE

Swarm measurements of lightning generated whistlers: an opportunity to sound the ionosphere

Martin Jenner[1], Pierdavide Coïsson[1], Gauthier Hulot[1], Dalia Buresova[2], Louis Chauvet[1] & Vladimir Truhlik[2]

[1] Université Paris Cité, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France
[2] Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czechia

Introduction

The three Swarm satellites measure the magnetic field of the Earth, up to 250 Hz during burst-mode campaigns. The detections in the Extremely Low Frequency (ELF) band of electromagnetic waves, called whistlers, caused by lightning strikes can help to sound the ionosphere below Low Earth Orbit (LEO).

Objectives :

- Extract knowledge on the ionosphere from whistlers in ELF
- Improve on the climatological predictions of the Ionosphere

ASM burst mode campaigns onboard Swarm

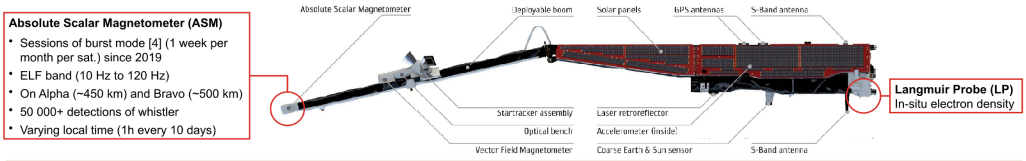

Figure 1: One of the three satellites of the Swarm mission and its instrumentation

Whistlers

A lightning strike generates a wide-band impulse that propagates in the Earth-Ionosphere waveguide. The ELF components can travel for thousands of kilometers.

Some of the power leaks into the ionosphere forming whistler waves. They propagate upward following the Earth magnetic field.

Their ELF components are detected by the ASM onboard the Swarm satellites (fig.2).

The ionosphere is a dispersive environments that causes the characteristic whistling shape. The dispersion D is related to the ionosphere composition [3].

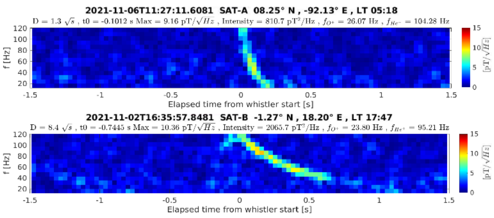

Figure 2: Examples of spectrograms of whistlers detected by the Swarm satellites

Total Root Electron Content

1. Propagation hypotheses:

- Extremely Low Frequency (ELF) propagation
- Plasma: neutral, cold, collision-less, 1D, e^- and O^+
- Quasi-Longitudinal propagation [3] above O^+ gyro-frequency

2. Approximation of the refractive index of Stix [6]:

$$n^2 \simeq \frac{f_{pe}^2}{f_{ge}(f + f_{gi})}\left(1 + \frac{\psi^2}{2}\right)$$

f_{pe} : e^- plasma frequency $\quad$ f_{ge} and f_{gi} : e^- and O^+ gyro-frequencies

3. Group delay T of the signal:

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

N_e : e^- density $\quad$ S : ray-path length $\quad$ ψ : wave normal angle

4. Total Root Electron Content (TREC)

The group delay of the whistler is proportional to the TREC:

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

TREC extraction from whistlers

The group delay T of whistlers is directly related to the TREC along the ray-path. T is difficult to measure since we don't know the time of emission of the wave.

1. Dual frequency approach

Instead we measure the time lag ΔT between the arrivals of two chosen frequencies f_1 (60 Hz) and f_2 (120 Hz).

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

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

2. Forward modelling with ray-tracing

We estimate the ray-path S and the parameters γ_{12} and b_{12} with ray-tracing [7]. It models the propagation in the environments provided by the following:

- Ionosphere: International Reference Ionosphere (IRI) 2016 [2]
- Magnetic field: 13th International Geomagnetic Reference Field [1]

The ray-path S is computed from the results of ray-tracing runs at both f_1 and f_2 . We can now also give an estimation of γ_{12} and b_{12}

3. TREC extraction (fig.3)

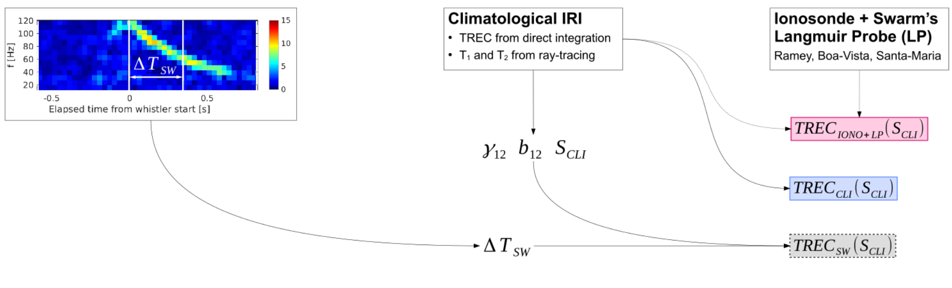

Figure 3: Diagram of the TREC extraction method from the whistler detected by Swarm. Comparison with the climatological IRI and the Ionosonde and the LP observations

Validation

We compare the results to TREC values obtained through integration of profiles from ionosondes station (fig.4).

The topside of each profiles are corrected with NeQuick2 [5] using the electron density of the LP as anchor point

Choice of the stations:

- Geomagnetic latitude
- Events within 500 km
- Less than 7.5 min from the closest profile

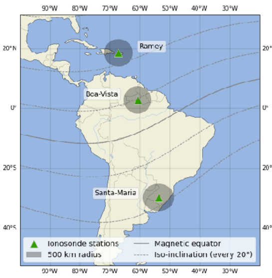

Figure 4: Ionosondes and area of selection of whistlers detections.

Results

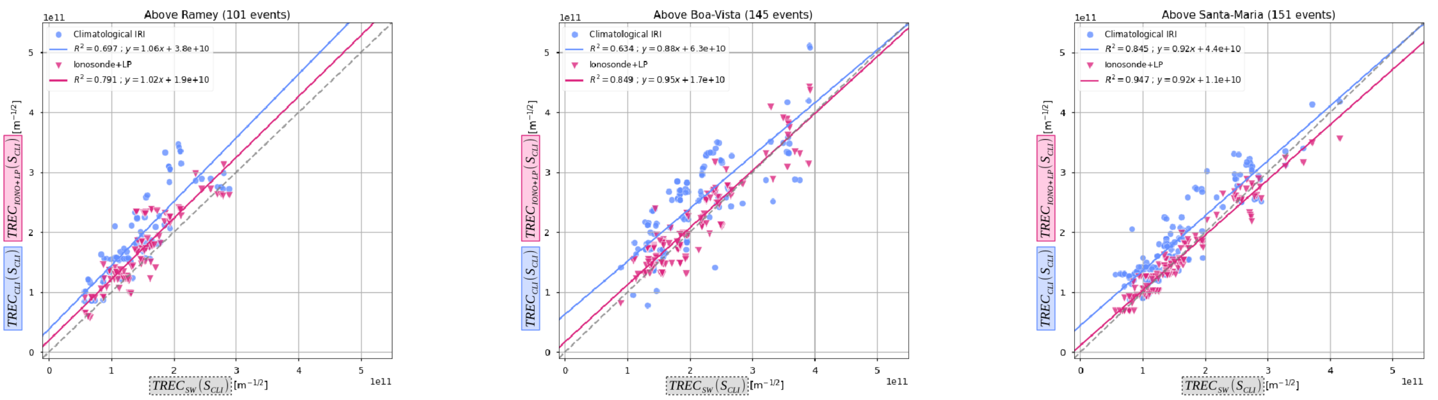

Figure 5: Result of the TREC extraction method on the selected events above the ionosondes. *Abscissa*: TREC estimated with the extraction method. *Ordinates*: TREC from the climatologic IRI and from the ionosondes and LP observations

Conclusions

The TREC is a new, valuable, measurement of the ionization state of the ionosphere. The method presented in this poster allows for a good recovery of the TREC. The values obtained on examples chosen for validation are consistent with the values derived from ionosondes soundings. Furthermore they bring improvements over the climatological values obtained from IRI.

References

[1] Alken, P. et al. (2021). *International Geomagnetic Reference Field: The thirteenth generation.* Earth, Planets and Space, 73 (1), 49. doi: 10.1186/s40623-020-01288-x183
[2] Bilitza, D. et al. (2017). International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. Space Weather , 15 (2), 418–429. doi: 10.1002/2016SW001593
[3] Helliwell, R. A. (1965). *Whistlers and Related Ionospheric Phenomena.* Stanford, California: Stanford University Press.
[4] Léger, J.-M. et al. (2015). *In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites.* Earth, Planets and Space, 67 (1), 57. doi: 10.1186/s40623-015-0231-1
[5] Nava, B. et al. (2008). *A new version of the NeQuick ionosphere electron density model.* Journal of Atmospheric and Solar-Terrestrial Physics, 70 (15), 1856–1862. doi: 10.1016/j.jastp.2008.01.015
[6] Stix, T. H. (1992). *Waves in plasmas.* New York: American Institute of Physics.
[7] Yabroff, I. (1961). *Computation of whistler ray paths.* Journal of Research of the National Bureau of Standards, Section D: Radio Propagation, 65D(5), 485. doi: 10.6028/jres.065D.061