Siffleurs à fréquences extrêmement basses détectés en orbite basse : résultats de campagnes d'acquisition de la mission Swarm et perspectives d'observation ionosphérique

Whistlers in Extremely Low Frequencies detected at Low Earth Orbit: results from Swarm mission acquisition campaigns and prospects for ionospheric observation

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Résumé/Abstract

Les magnétomètres scalaires absolus (ASM) à bord des satellites de la mission Swarm de l'Agence Spatiale Européenne (ESA) peuvent acquérir des données en mode *burst* avec un échantillonnage à 250 Hz. Depuis 2019 des campagnes d'acquisition en mode *burst* ont été réalisées tous les mois avec deux des trois satellites de cette constellation : Alpha (altitude orbitale autour de 450 km) et Bravo (altitude orbitale autour de 500 km). Ces satellites ont la caractéristique de dériver progressivement en heure locale (LT), environ 1 heure tous les 10 jours. Ceci a été exploité pour couvrir progressivement toutes les LT, avec l'objectif d'obtenir une couverture complète de toutes les LT pour toutes les saisons. Ces campagnes ont déjà permis de détecter plus de 90 000 siffleurs, produits par les éclairs les plus forts. Des algorithmes spécifiques ont été développés pour détecter et caractériser ces siffleurs. Un catalogue d'événements est maintenant distribué comme un produit officiel de la mission Swarm. Nous avons aussi développé une technique qui utilise les siffleurs détecter pour obtenir un nouveau paramètre ionosphérique : le Contenu Électronique Racine Total (TREC).

Absolute Scalar Magnetometers (ASM) onboard the satellites of the European Space Agency (ESA) Swarm mission can be run in a 250 Hz sampling rate *burst* mode. Since 2019, one-week *burst* mode acquisition campaigns have been carried out every month by each of two of the three satellites of the constellation: Alpha (orbital altitude around 450 km) and Bravo (orbital altitude around 500 km). These satellites have the characteristics of drifting progressively in Local Time (LT), about 1 hour every 10 days. This has been used to progressively cover all LTs, the goal being to obtain full LT coverage at all seasons. These campaigns already allowed the detection of more than 90 000 whistlers, produced by the strongest lightning strikes. Dedicated algorithms to detect and characterise these whistlers have been developed and a catalogue of events is now distributed as an official scientific product of the Swarm mission. We also developed a technique that takes advantage of the detected whistlers to obtain a new ionospheric parameter: the Total Root Electron Content (TREC).

1 Introduction

The ESA Swarm mission completed 10 years in orbit at the end of 2023. In addition to achieving its main scientific objectives of monitoring the Earth magnetic field, several other new scientific products have been developed. The ASM measures the intensity of the magnetic field at the location of the satellite. It is nominally operated at 1 Hz, but when operated in *burst* mode at 250 Hz [1], proved to be able to detect electromagnetic signals in the Extremely Low Frequencies (ELF). Regular acquisition campaigns in *burst* mode started in 2019 and continue today, one week per month on both the Alpha and Bravo satellites. This constitutes a very high-quality dataset, covering now both low and high solar activity conditions, at all local times. We focused our studies on lightning-generated whistlers, and analyzed in details the propagation characteristics of these signals, with the aim of developing new techniques to obtain information on the ionosphere through which they travel.

2 Methods and results

2.1 Detecting whistler signals in ELF

Fractional-hop whistlers are usually short signals, lasting at most a few seconds, depending on their dispersion. We trained an Adaptive-Network-based Fuzzy Inference System [2], in order to detect most of these events without the need of human screening of the whole dataset. We started from manually-identified whistler events and selected some features that can be computed from the time series of magnetic field intensity, corrected for a polynomial fit to remove large-scale structures, as well as from the corresponding power spectral densities. Whistlers can be recognized as lowering tone signals; an example is provided in Figure 1.

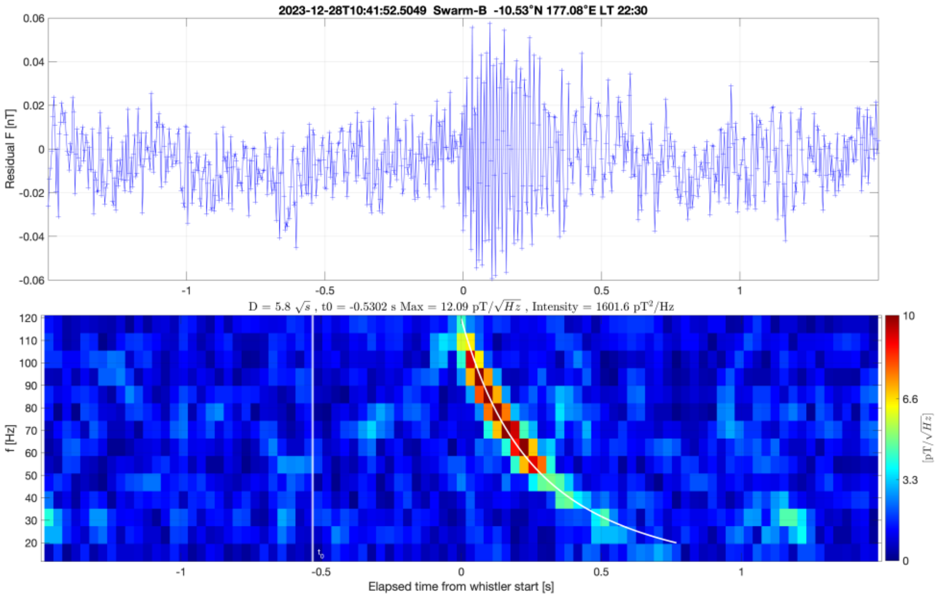

Figure 1 Example of whistler detected by Swarm B on 28 December 2023. Top panel: time series of ASM burst data after removing a polynomial fit. Bottom panel: power spectral density plot of the whistler. The dispersion curve is superposed in white and the vertical line at -0.5302 s represent the estimated time when the whistler signal entered the ionosphere.

Currently this system is used to detect time-windows within which whistlers signals are present. A subsequent manual analysis is performed to recover physical parameters: dispersion, estimated time when the signal entered the ionosphere, signal intensity, as illustrated in the bottom panel of Figure 1. This dataset is publicly distributed at https://swarm-diss.eo.esa.int/#swarm/Level2daily/Entire_mission_data/WHI.

2.2 Spatial and LT occurrences of whistlers in the ELF

The data available so far allow to obtain some information on the global occurrences of these signals. Figure 2 shows that the spatial distribution of whistlers mainly reflects regions where the most intense thunderstorms with lightning activity occur at the surface of the Earth. The ELF component of lightning signals can nevertheless travel several thousands of kilometers in the Earth-ionosphere waveguide before entering the ionosphere, broadening the regions where whistlers can be detected. Very close to the magnetic equator the number of detected whistlers drops. This is an indication that ionospheric propagation does not allow whistlers to propagate up to the satellite height, when the local Earth magnetic field is nearly horizontal.

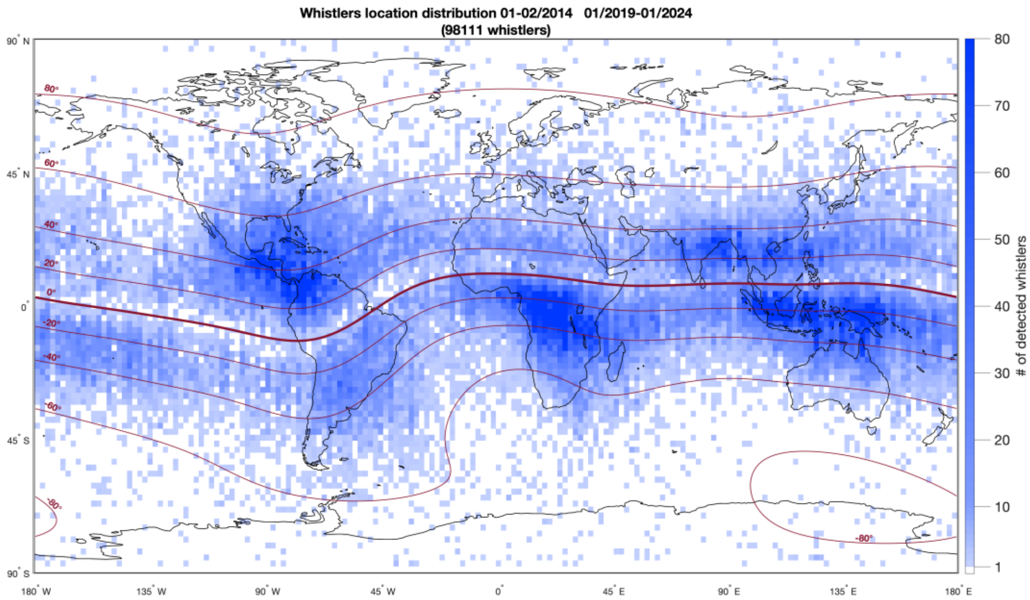

Figure 2 Density map showing the total number of detections within areas of 2°x2° in latitude-longitude throughout all of Swarm burst-mode campaigns run so far. Magnetic inclination isolines are also shown in red.

A first distribution of daily occurrences as a function of detection local time for each season is shown in Figure 3. The diurnal peak close to the sunset (between 18 and 19 LT) is present at all seasons, and is particularly strong between December and May. Very low whistler activity is recorded during day-time.

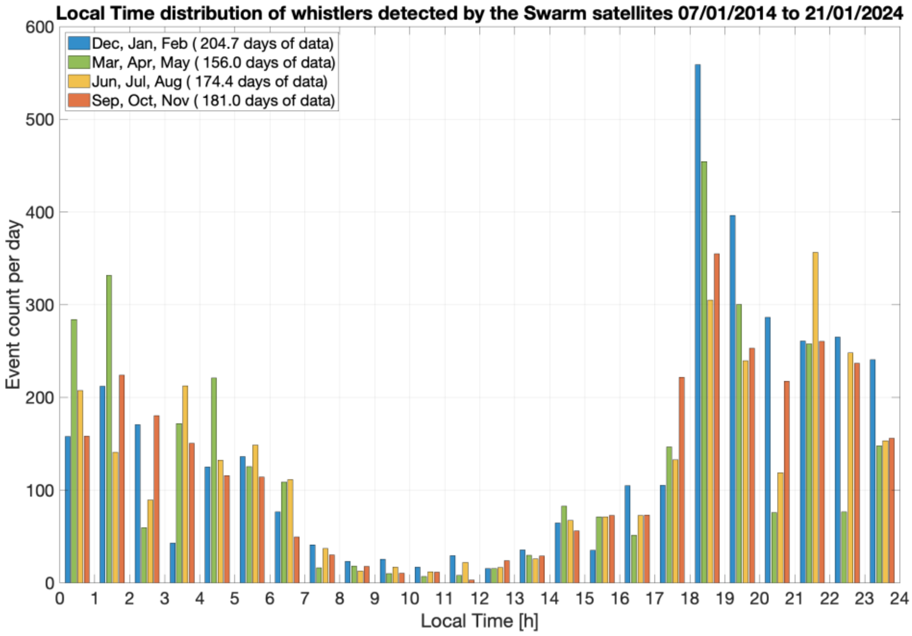

Figure 3 Average number of whistlers detected during each local time hour at the various seasons. Acquisition campaigns of one week per month per satellite were conducted on Swarm Alpha and Bravo.

A comparison with the distribution in LT of powerful lightning strikes was conducted using data from the World Wide Lightning Location Network (WWLLN) [3]. Figure 4 shows the total number of lightning strikes exceeding specific levels of energy, when available from WWLLN. The diurnal pattern shows a similar variation as the one observed for the whistlers, but presents a secondary peak in the afternoon, which is not present in the whistler data. This is an indication that the ionospheric conditions during day-time are not favorable for the penetration of ELF signals in the ionosphere.

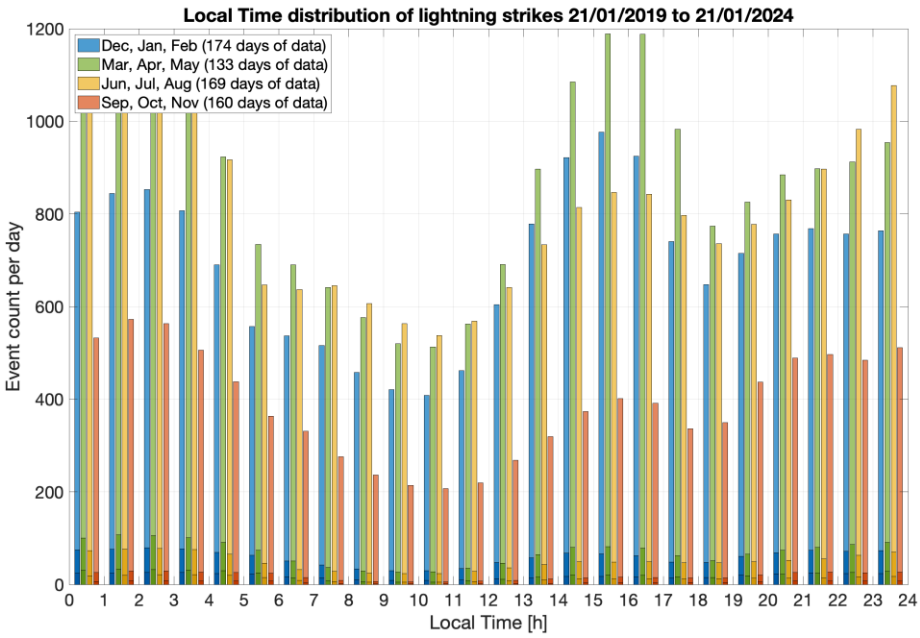

Figure 4 Global distribution of lightning strikes during 4 seasons recorded by WWLLN at each LT during the days when the ASM were operated in burst mode between January 2019 and January 2024. Darker shades of colors identify three levels of lightning energy: light colors >10 000 J, medium colors >50 000 J, dark colors >100 000 J.

2.3 Measuring the ionosphere from whistler signals in ELF

We recently developed a novel technique to exploit whistlers' characteristics to recover information on the ionospheric plasma crossed by the whistlers [4]. Under the hypothesis of ionospheric plasma composed essentially of ions O^+, for ELF signals below the lower hybrid frequency and above the oxygen gyrofrequency, we analyzed the index of refraction in the ionosphere. We obtained that the travel-time of each whistler frequency is very close to be proportional to the integral of the square-root of the electron density. We called this parameter Total Root Electron Content (TREC):

$$\mathrm{T}REC = \int_a^b \sqrt{N(s)}\mathrm{d}s \qquad (1)$$

where $N(s)$ is the electron density along the whistler's propagation path s from a point a at the base of the ionosphere and the detection point b. In this frequency range the propagation path is not a straight line. The wave vector at ELF maintains a nearly constant angle with the ambient magnetic field direction. The propagation path is nearly vertical at high and mid latitudes, but progressively bends at low latitude, explaining also the lack of detections very close to the magnetic equator at Swarm satellites altitude. The propagation path can be computed by using ray-tracing algorithms.

We were able to validate this concept by using ionospheric profiles from nearby ionosondes [4], demonstrating that whistlers can be used to measure TREC below Swarm satellites.

3 Conclusions

Natural whistler signals in the ELF can be detected at LEO altitudes, more frequently at low latitudes and in the evening hours. The dispersion of lightning-generated whistlers can be used to infer the amount of plasma crossed while travelling through the ionosphere. This technique has been applied to Swarm *burst* mode data and could be exploited by future missions with whistler detection abilities, such as the recently selected NanoMagSat constellation of the Scout program of ESA (https://www.esa.int/Applications/Observing_the_Earth/FutureEO/NanoMagSat_and_Tango_Scout_missions_get_go-ahead).

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