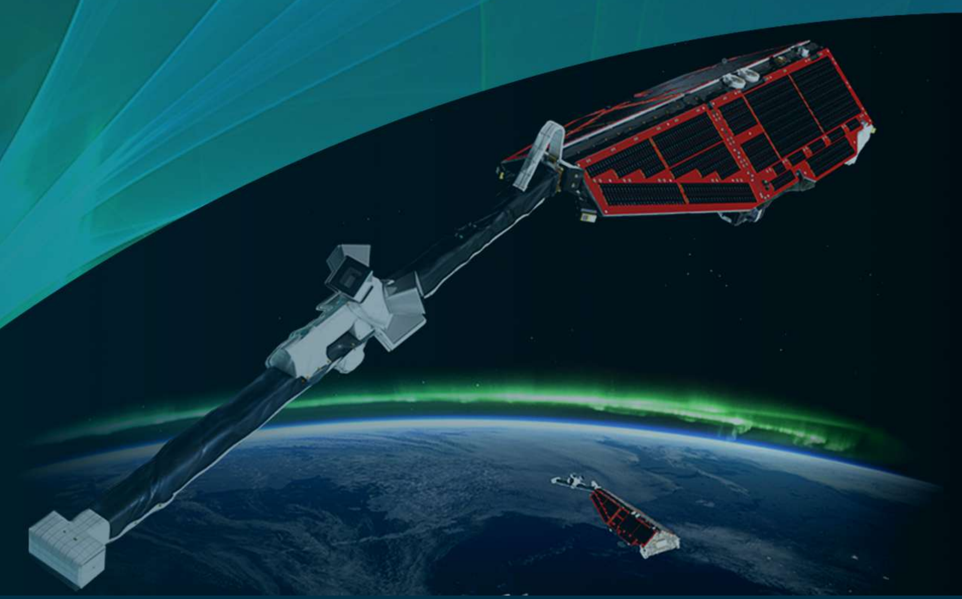

100 000 whistlers detected during ASM burst mode campaigns: uncovering seasonal and solar cycle dependencies

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1 Introduction

Since 2019, the Absolute Scalar Magnetometers (ASM) of Swarm Alpha and Bravo acquired every month one week of data in burst-mode. The Local Time of the Ascending Node of these satellites drift by about one hour every ten days, therefore each campaign covered a specific temporal sector. Over the years, a complete coverage of all local times has been achieved. Recently, this coverage has been extended to all local times for each season. The acquisition campaigns started during the minimum of the solar cycle, and keep being acquired during the current solar maximum. When the Swarm satellites were in close counter-rotating orbits, several overlapping acquisition campaigns were also conducted in 2021 and 2022.

We process these data to detect and characterise whistler signals in the Extremely Low Frequencies (ELF). Whistler data are now distributed as level 2 scientific product of the mission. The corresponding files include their dispersion, their intensity and the estimated time when these signals entered the ionosphere. The dataset exceed now 100 000 whistlers events.

Global statistics of whistler occurrences reveal their geographical, local-time, seasonal and solar activity dependencies. These correlate with the lightning activity in the troposphere, with powerful strikes being able to generate whistlers detected several thousands of km away, since ELF signals can propagate at very far distance in the waveguide between the ground the lower ionosphere. We used data from the World Wide Lightning Location Network (WWLLN) and the World ELF Radiolocation Array (WERA) to identify the strikes that originated remarkable whistlers.

We present remarkable whistler events and discuss the propagation properties of these signals.

2 Global seasonal whistler distribution

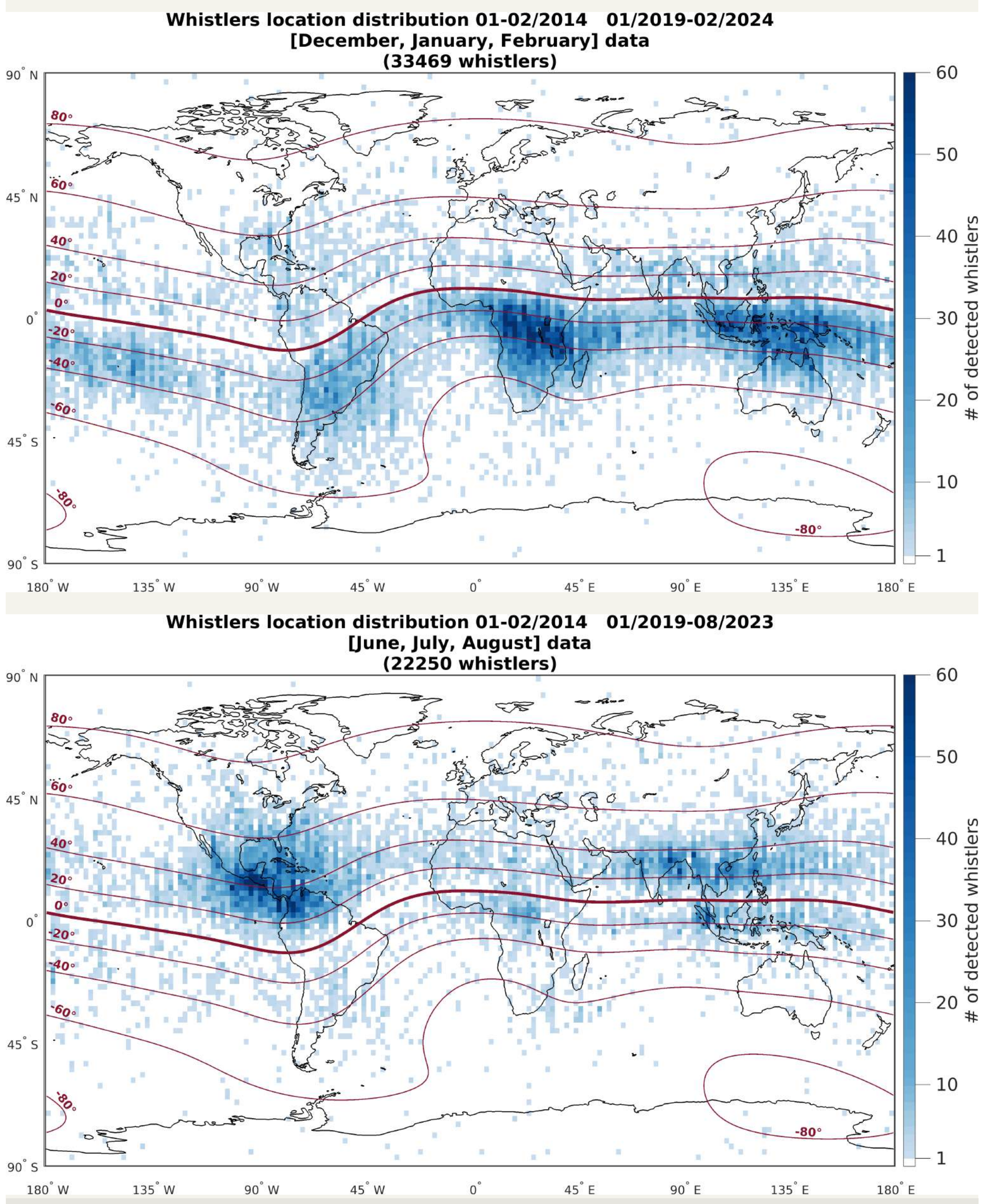

Figure 1: Global distribution of whistlers detection in the ELF.
Top panel: detections during December-January-February months.
Bottom panel: detections during June-July-August months.
Gridding 2°x2° in latitude and longitude. Isolines of magnetic inclination are displayed in red.

- Whistlers in the ELF are predominantly detected at low latitudes.
- There is a marked seasonal hemispheric asymmetry (Figure 1)
- Equinoctial months (not displayed here) present intermediate whistler distribution.
- The regions with the highest number of detections correspond to the regions where most lightning strikes occur: central America, central Africa and Indonesia.
- The propagation conditions close to the magnetic equator are not favorable for whistlers to penetrate in the ionosphere up to Swarm height.
- Whistler can be detected several thousands km away from the lightning strike location.

3 Strongest whistler

Usually the amplitude of the whistler is signal ~0.1 nT, but exceptional events can exceed 1 nT. The strongest whistler detected so far occurred on 16/02/2022, with a maximum amplitude of 1.5 nT (Figure 2).

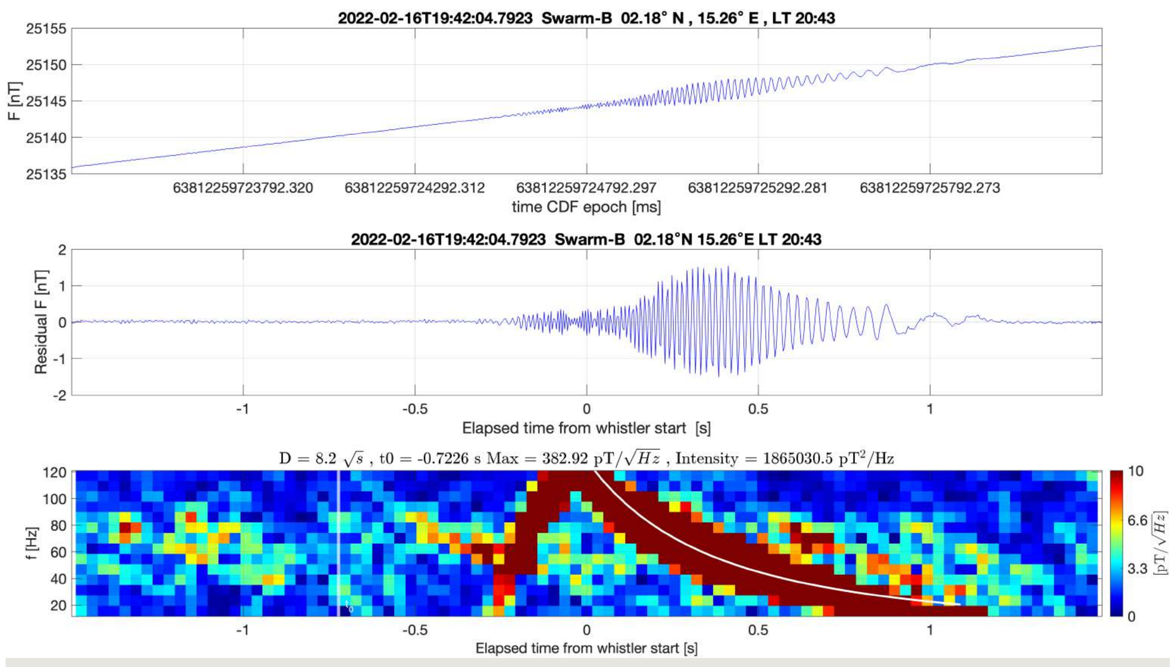

Figure 2: Strongest whistler detected by Swarm. Top panel: ASM time series. Middle panel: residual F after removal of a 4-degree polynomial.
Bottom panel: PSD of the whistler signal. Note the folding of whistler frequencies higher than the 125 Hz Nyquist frequency.

4 Diurnal variation according to seasons

At the end of 2023 data acquisitions at all local times during all seasons reached a complete coverage, even if not homogeneous. The diurnal variation is similar in all seasons, with a marked peak around sunset hours. Numerous whistlers can be detected during the whole night, while around noon only few events occur.

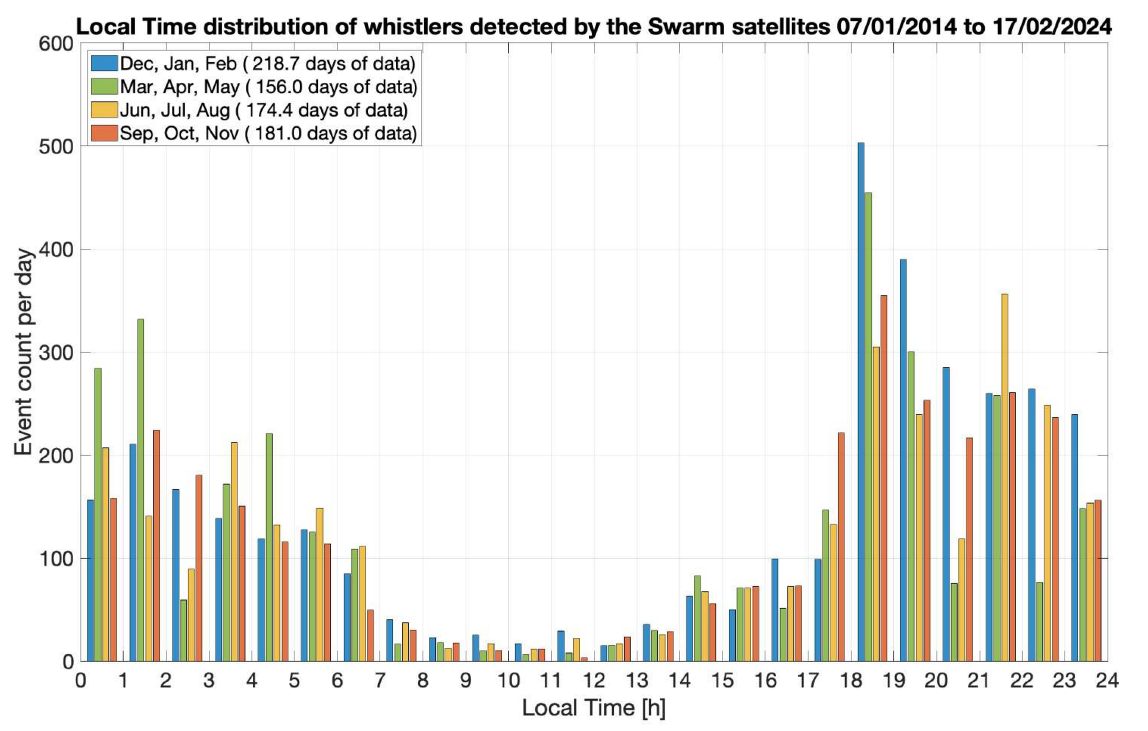

Figure 3: Average number of whistlers detected during one day as function of Local Time for the various seasons.

5 Lightning activity in the troposphere

Lightning strikes are measured on the ground in VLF by the World Wide Lightning Location Network (WWLLN). Only the strongest strikes generate whistlers detectable at Swarm altitude, but it is still unclear which are the conditions favorable for ionospheric penetration. The night-time peak of lightning activity and minimum around noon corresponds to the whistler's pattern, however the secondary peak around 15 LT does not correspond to an increase in whistler activity. The secondary minimum around 18 LT is in contrast with the maximum whistler occurrences.

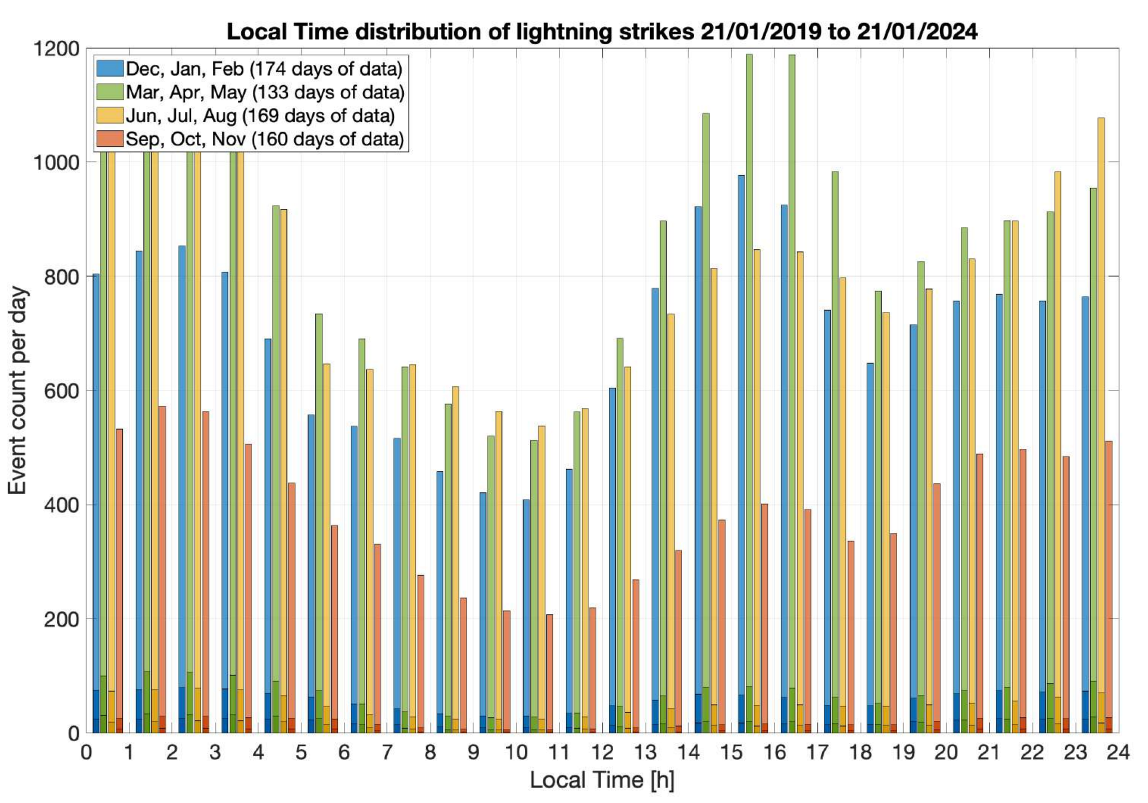

Figure 4: Number of lightning detected by WWLLN during the days of ASM burst-mode acquisitions as function of the Local Time of the strike. Different shades correspond to lighting energy >10 000 J, >50 000 J, >100 000 J.

6 Solar cycle dependency

Regular burst-mode sessions started during solar minimum conditions. The increase of solar activity has been well correlated with an increase in the number of detected whistlers (Figure 5).

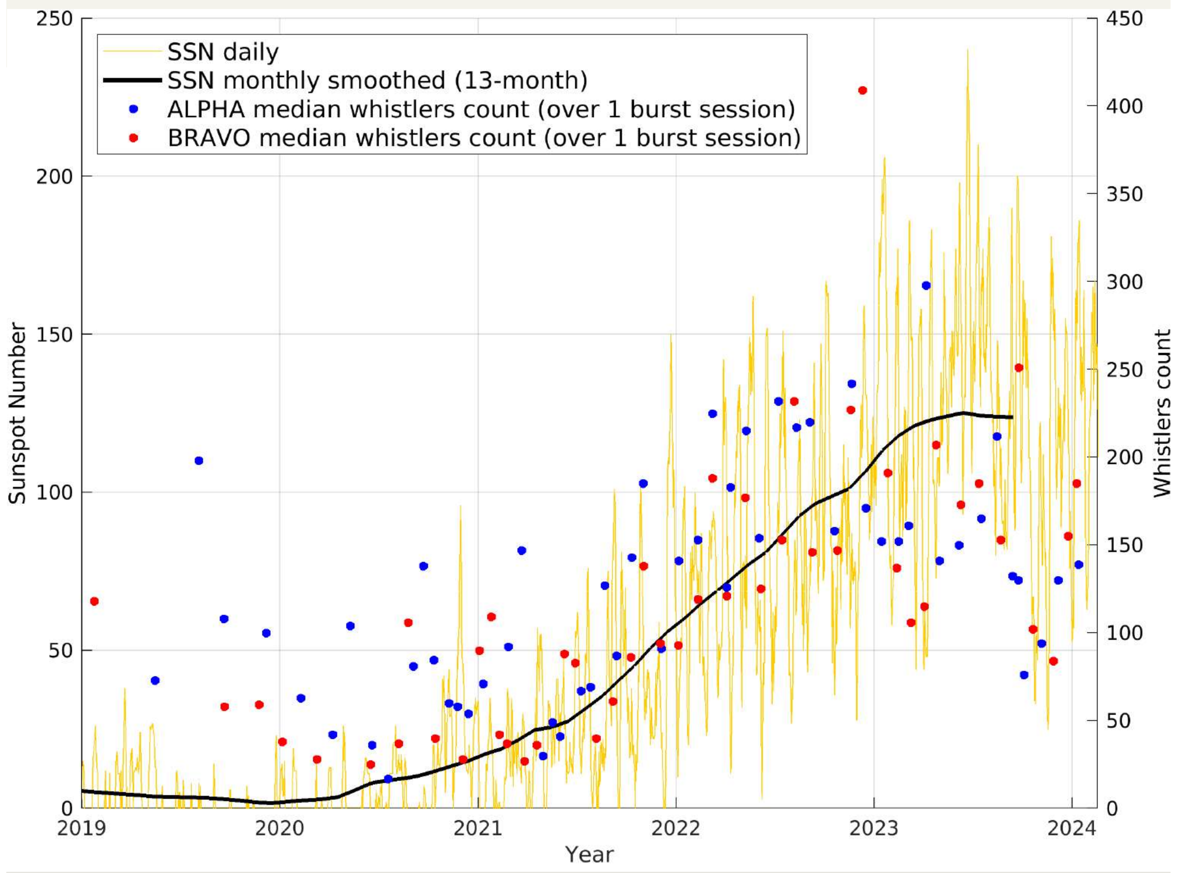

Figure 5: Median number of whistlers detected during 1-week ASM burst sessions and daily and smoothed sunspot number between January 2019 and February 2024.

7 Propagation conditions

Lightning signals cover the whole spectrum of electromagnetic waves. The wave-guide between the ground and the ionosphere allows ELF signals to propagate at very far distances all around the globe. Part of the signal can leak into the ionosphere. Simultaneous detections by Alpha and Bravo satellites were achieved during the counter-rotating phase of the mission.

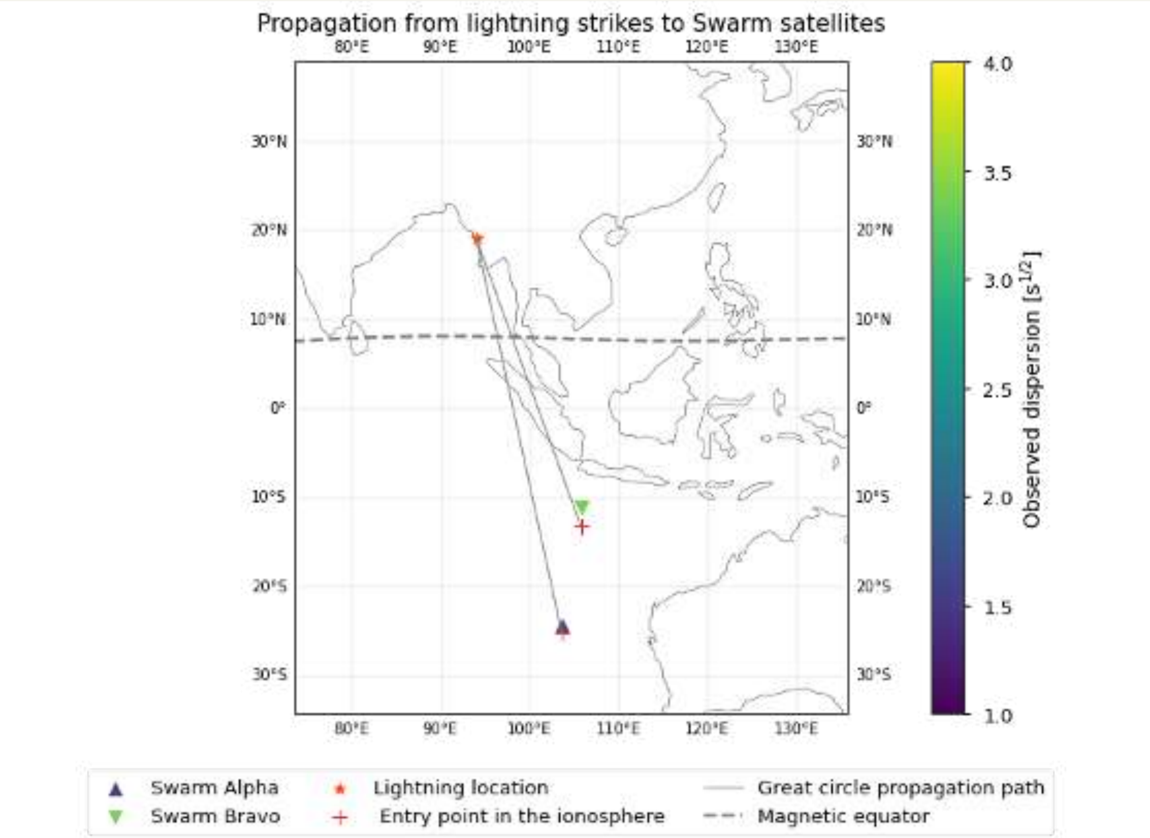

Figure 5: Identification of lightning strike that originated whistlers detected by both Alpha and Bravo satellites from WERA ELF data. The signal propagated in the waveguide from the Northern to the Southern hemisphere, before penetrating in the ionosphere and reach Swarm satellites.

Conclusions

- A total of 737 days of ASM burst mode campaigns has been acquired and analysed.
- 100517 whistlers have been detected and characterised.
- This dataset covers all local times at all season, however the coverage is inhomogeneous.
- Whistlers in ELF are more likely to be detected around sunset hours.
- A large day-to-day variability in the number of detections is observed.
- A seasonal hemispheric asymmetry, with the highest number of events in the summer hemisphere..
- A peak in whistlers occurrences have been found in the rising phase of the solar cycle.

Acknowledgements

Data used in this study were obtained from:

- Swarm whistlers: https://swarm-diss.eo.esa.int/
- Sunspot numbers from WDC SILSO: https://www.sidc.be/SILSO/home
- WWLLN lightning locations: http://wwlln.net/
- WERA ELF data: http://www.oa.uj.edu.pl/elf/index/projects3.htm