Capabilities of the Swarm magnetometers to detect events related to lightning activity

AGH & CBK & OBSEE

MS2
ESRIN

October 21, 2019

Agenda

Swarm for TLEs (Transient Luminous Events)

- **Capabilities of the Swarm magnetometers to detect events related to lightning activity** - Approach to the problem, main goals and review of selected results - Synergies with other satellite mission.
- Swarm measurements and lightning activity: minimum variance and inter-satellite cross-correlation analysis (Marek Strumik, CBK)
- Searching for correlations between magnetic field variation on Swarm and atmospheric discharges observed by ELF ground stations (Janusz Mlynarczyk, AGH)
- Remarks on the "whistler" type waves registered in space (Jan Blecki, CBK)

Scope of the study

- Registrations from Swarm ASM Burst mode data (250 Hz) proved to be effective in detection signatures of lightning
- **Is is possible to detect with Swarm magnetometers, signals related to such lightning discharges that are accompanied by strong luminous events (Transient Luminous Events - TLEs)?**
- Believed to be rather rare - High-speed cameras many evidences provided on regular basis

Plenty of daily updates with Jets:

https://twitter.com/paulmsmithphoto

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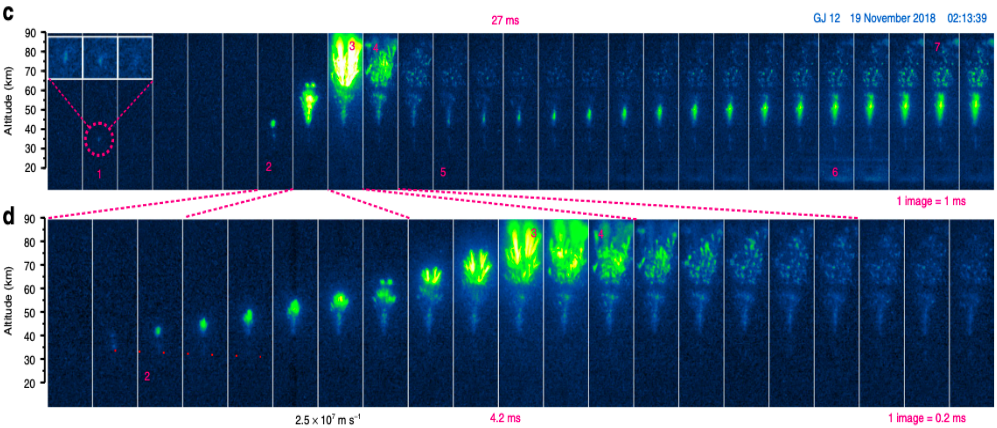
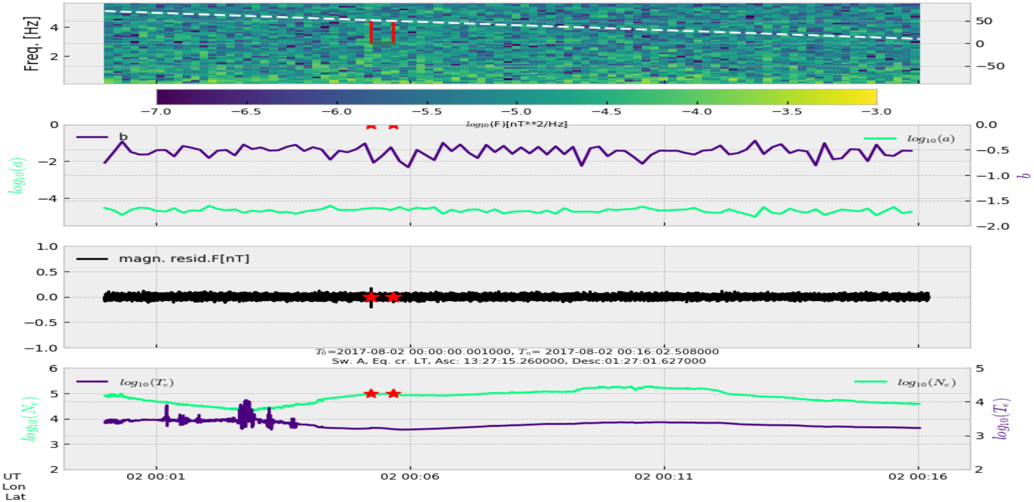
Problem of interest

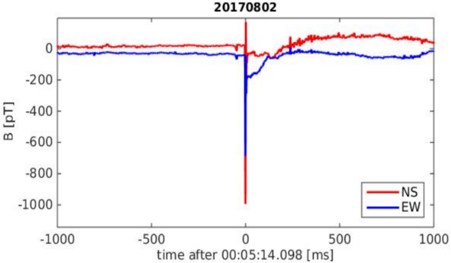


Gigantic jet discharges evolve stepwise through the middle atmosphere
-`https://doi.org/10.1038/s41467-019-12261-y`

Problem of interest



Problem of interest - Documented with ground-based observation



Strongest event, with charge moment **4870** C km, should be seen on Swarm, if there is conjunction with the location of the satellite.

Spectral analysis from Swarm MAGx_HR - Processing steps

Powerful discharges (CG+ type) may generate strong currents which will lead to small-scale fluctuations in the **B** field

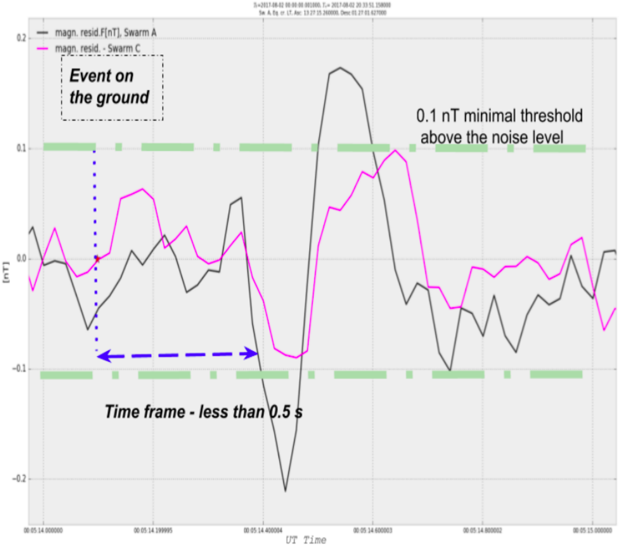
- Local **B** trend removal - Approximation based on 4^{nd} order polynomial
- derive residuals

$$\delta B_i = B_i^{obs} - B_i^{approx}$$

  for FFT
- 128/256 samples, used for FFT spectrum;
- Spectrum up to 25 Hz, for three components and scalar component of the magnetic field for visual inspection;
- Analysis concentrates on residual signal and sudden peaks which have magnitude higher than assumed threshold ($\delta F > 0.1$ nT).

Revised approach

- Expected signal - differentiated Gaussian signal
- minimal threshold for detection - above $\pm .1nT$
- analysis of scalar field δF - not components
- looking for a source of currents
- automatic detection - quality of the fit determines, whether the spike is a good candidate for further analysis



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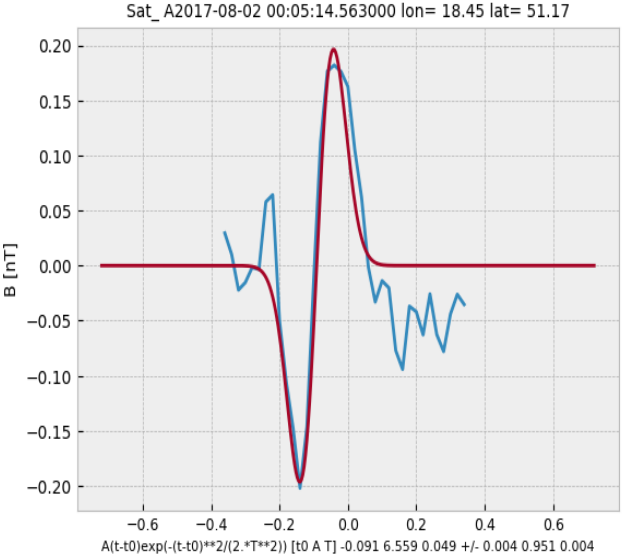
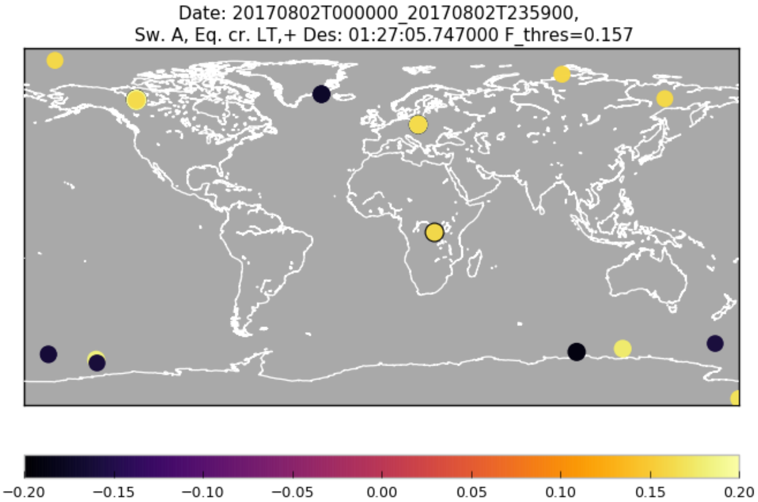
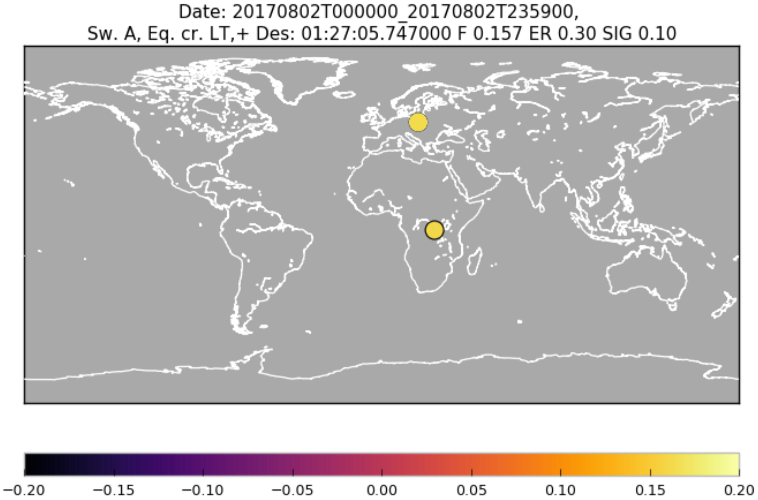


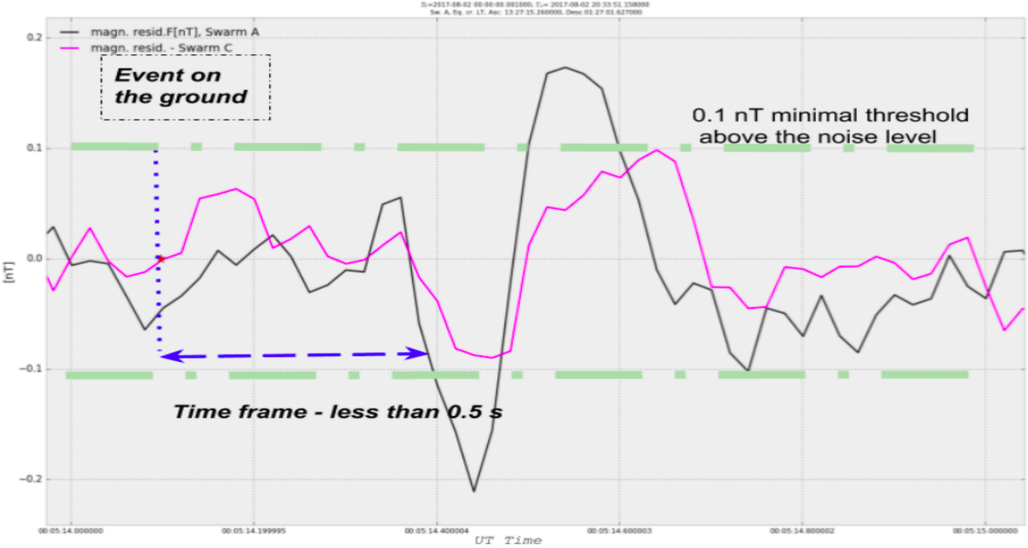
Defining additional criteria



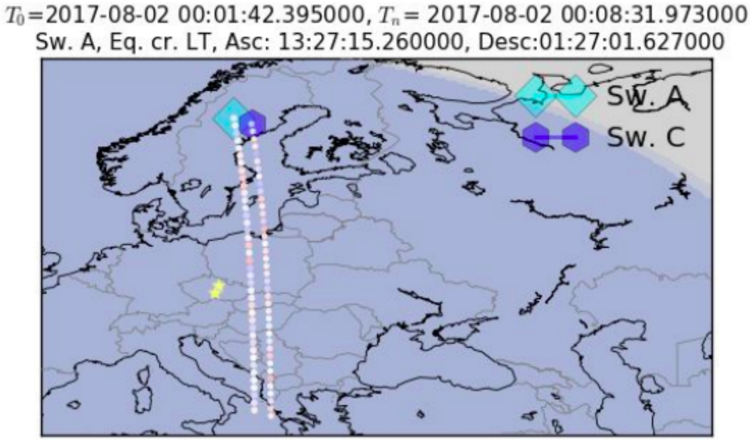
Defining additional criteria - synchronization with database of lighting



Swarm A/C - Why the effect is only on one satellite



Swarm A/C - Distance between event and the satellite track



Fields and Radiation of a Localized Oscillating Source - Defining geometry condition based on the physical problem of "Fields and Radiation of a Localized Oscillating Source"

Assumption:

Based on the the Biot-Savart law magnetic field $B(t)$, at a distance r from a slowly varying lightning current J(t) with channel length l directly above a conducting surface and also with a second conducting surface (the ionosphere) located at height h_i.

Based on: *Classical Electrodynamics - Jackson*

Fields and Radiation of a Localized Oscillating Source - defining geometry condition

In the general approach we may consider the potentials, fields, and radiation from a localized system of charges and currents which vary sinusoidally in time. The real part of such expressions is to be taken to obtain physical quantities. The electromagnetic potentials and fields are assumed to have the same time dependence

$$\rho(x,t) = \rho(x)e^{-i\omega t}, \quad J(x,t) = J(x)e^{-i\omega t}$$

The solution for the vector potential $A(x,t)$ in the Lorentz gauge is:

$$A(x,t) = \frac{1}{c}\int d^3x \int dt' \frac{J(x', t')}{\|x - x'\|}\delta\left(t' + \frac{x - x'}{c} - t\right).$$

The Dirac delta function assures the causal behavior of the fields. Assuming sinusoidal time dependence A becomes:

$$A(x,t) = \frac{1}{c}\int J(x')\frac{e^{ik\|x-x'\|}}{\|x - x'\|}d^3x$$

Fields and Radiation of a Localized Oscillating Source - defining geometry condition

The magnetic induction: $B = \nabla \times A$, outside the source, the electric field is: $E = \frac{i}{k}\nabla \times B$.

Given a current distribution J(x'), the fields can be determined by calculating the integral for $A(x)$. Taking into account general properties of the fields in the limit that the source of current is confined to a small region (small - compared to a wavelength). If the source dimensions are of order d and the wavelength is $\lambda = \frac{2\pi c}{\omega}, and if \mathrm{d} \ll \lambda$, then there are three spatial regions of interest:

- **The near (static) zone:** $d \ll r \ll \lambda$
- The intermediate (induction) zone : $d \ll r \sim \lambda$
- The far (radiation) zone: $d \ll r \ll \lambda$

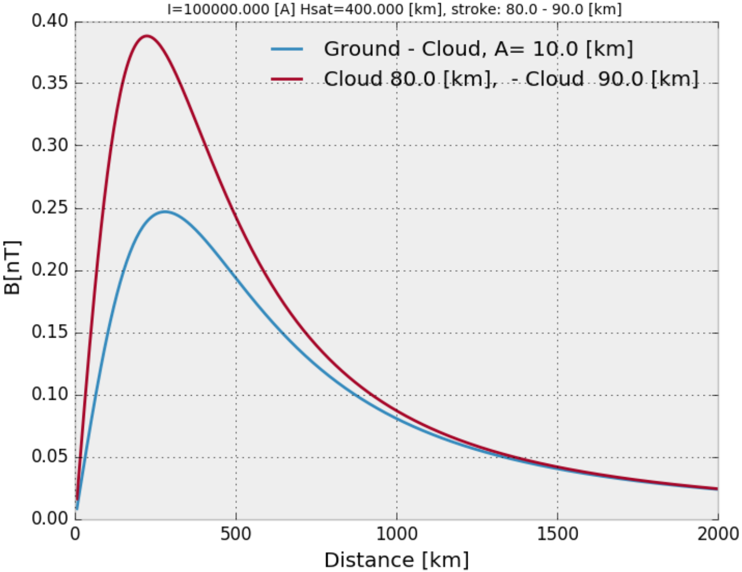
In the **near zone the fields have the character of static fields** with radial components and variation with distance which depends in detail on the properties of the source. In the far zone, on the other hand, the fields are transverse to the radius vector and fall off as r^{-1}, typical of radiation fields.

For the near zone where $d \ll r \ll \lambda$ (or $k \cdot r \ll 1$), the exponential part in $A(x, t)$

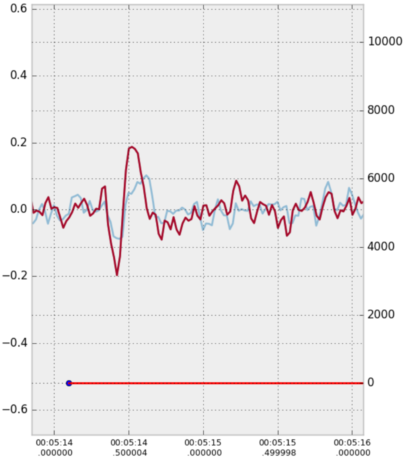
$$A(x,t) = \frac{1}{c}\int J(x')\frac{\overbrace{e^{ik\|x-x'\|}}}{\|x-x'\|}d^3x$$

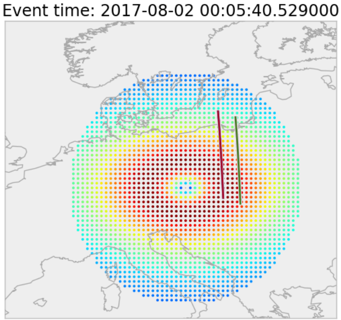
can be replaced by unity. This shows that the near fields are quasi-stationary, oscillating harmonically as $e^{-i\omega t}$, but otherwise static in character.

Geometrical condition for detection



Geometrical condition transformed on the Earth's surface around the location of the lightning event

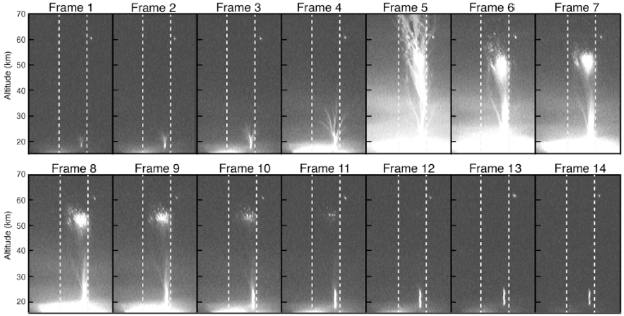




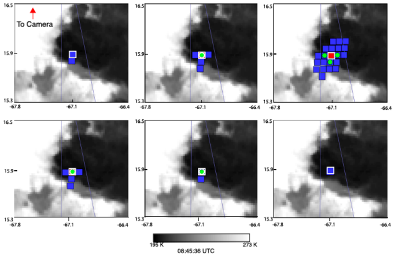
Review of selected cases

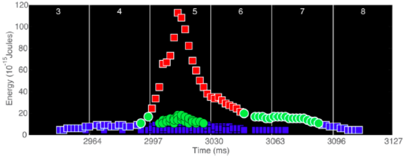
- Selection of results from the North and South Americas - cases, which can be verified with additional data from satellite mission
- A sample of results from Africa

Additional source of data - GLM



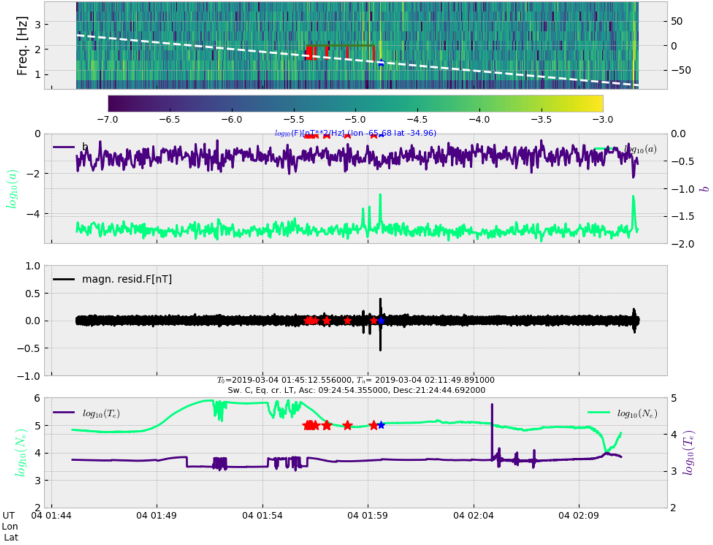
Low-light-level images of the 08:46 UTC gigantic jet on **19 August 2017**. Frame 1 - 08:46:02.864 UTC *Source: First Observations of Gigantic Jets FromGeostationary Orbit (Levi D. Boggs, doi:10.1029/2019GL082278*





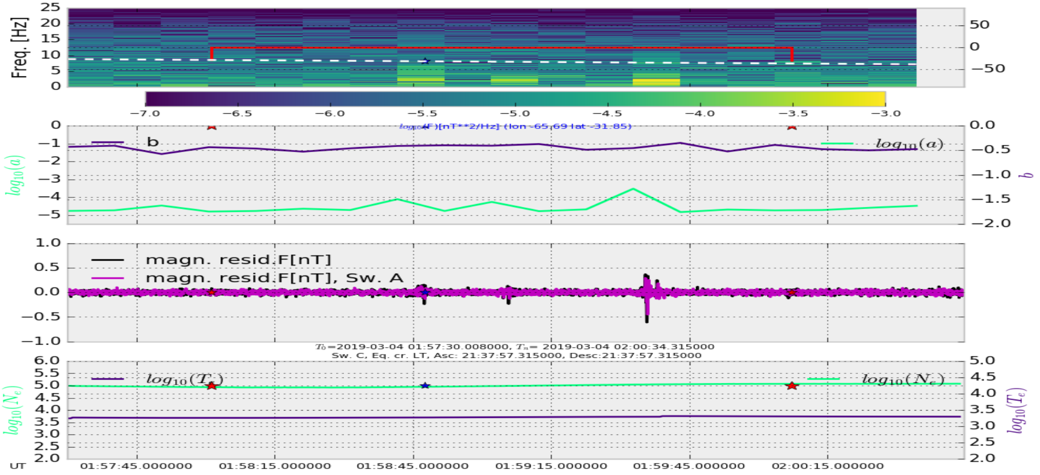
For flash on: 8:46:02 (462) UTC, Duration of series of events: 160 ms, Max event En: 112.9 (fJ), **Flash Max En. 3,067.2 (fJ)**

Thunderstorms in Patagonia - 20190304 - UTC 01:58:00

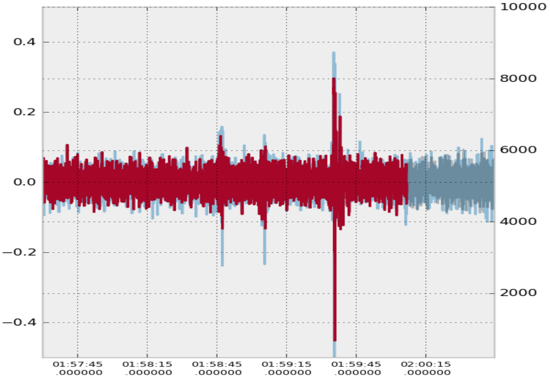


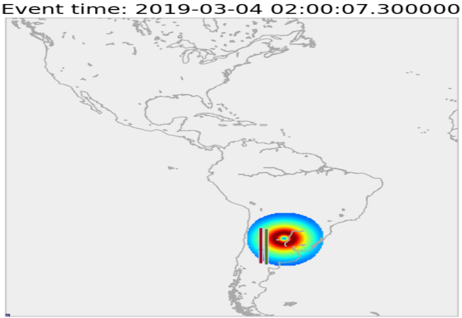
- Swarm passes through a series of prominent plasma depletions and enters the region of strong thunderstorm.
- Location and time of flashes derived from the GLM imager.

Thunderstorms in Patagonia - 20190304 - UT: 01:58:00 - Swarm A/C



Thunderstorms in Patagonia - 2019-03-04 - UT: 01:57:30





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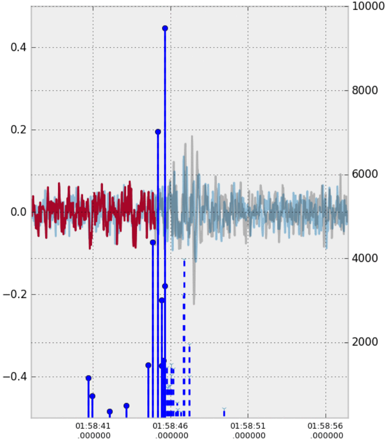

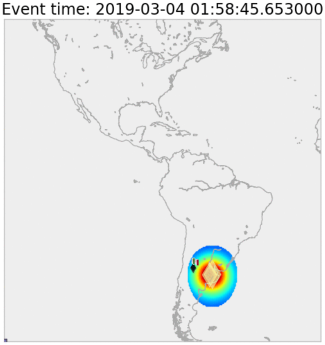

According to GLM data: T_0 = 04-Mar-2019 01:58:45.653, E_f = 9480.0 [fJ], duration = 0.675975 sec., first impuls on Swarm $T_{0,S}$ = 01:58:47.542, it gives **1.889 sec** delay. The largest peak occurs at: $T_{max,S}$ = 01:59:35.879 (Amp. -0.580 nT). Large delay **48.337 sec.** indicated that observed highest peak comes from the wave which was reflected in the IAR.

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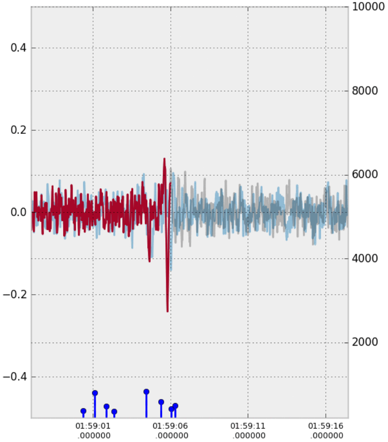

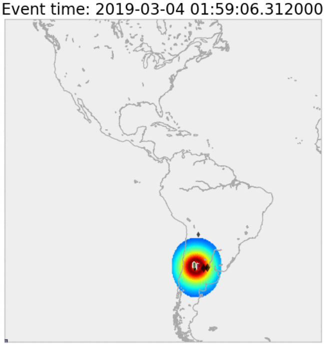

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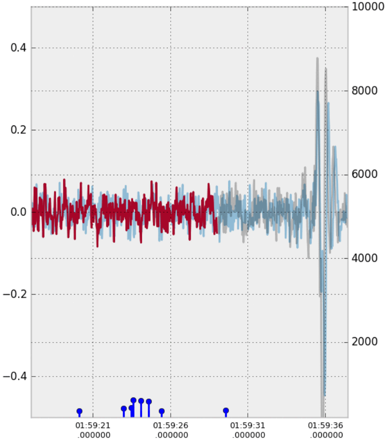

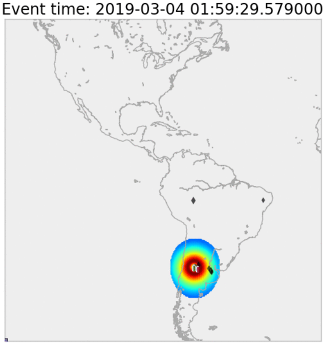

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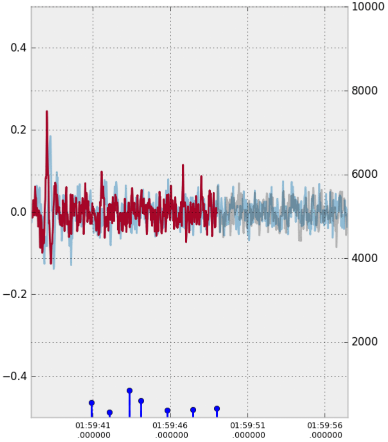

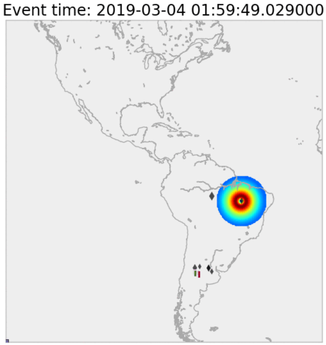

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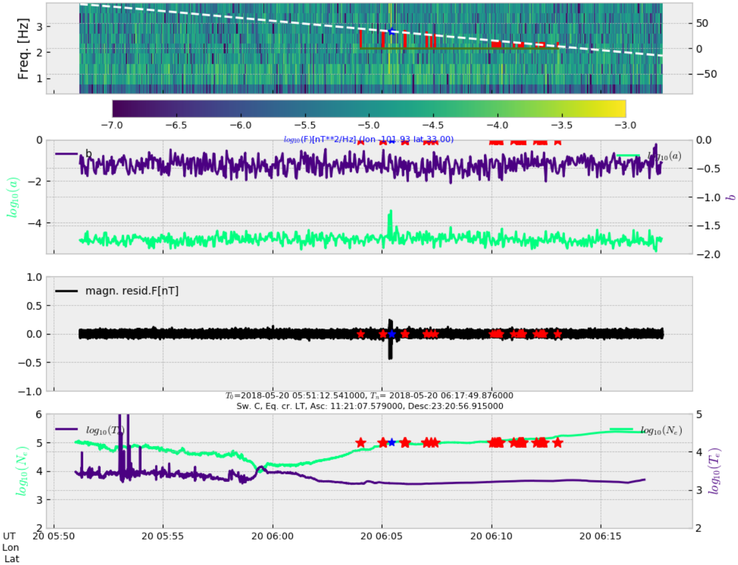
1-min sequence of combined registration of Swarm and GLM

Patagonia

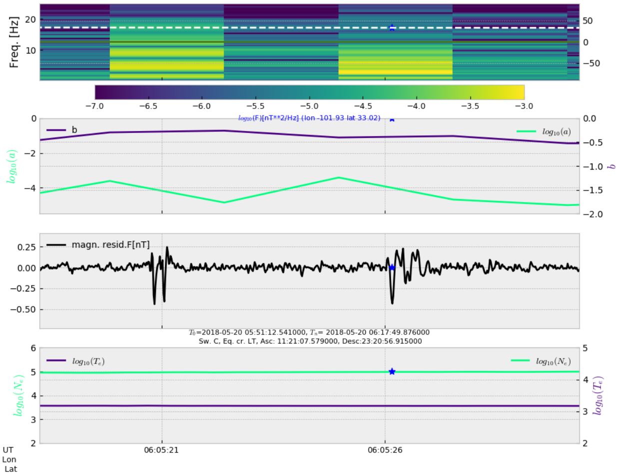
Thunderstorm in Patagonia - Summary

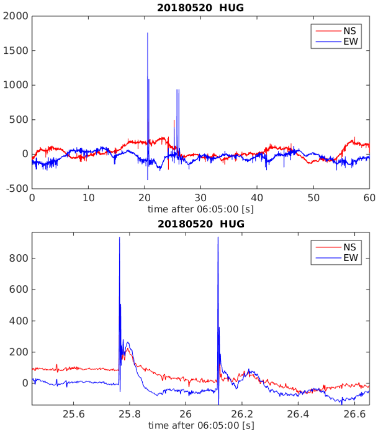
- GLM registration indicate that a series of strong discharges was observed at the time when Swarm was approaching the region.
- Large energies provided by the GLM imager, suggest that at least 4 Gigantic Jets could occur in the time frame of 1 min.
- Large delay **48.337 sec.** between the strongest event and most intense fluctuations registered by Swarm, indicate that observed highest peak comes from the wave which was reflected in the IAR.

Thunderstorms in Oklahoma - 2018.05.20

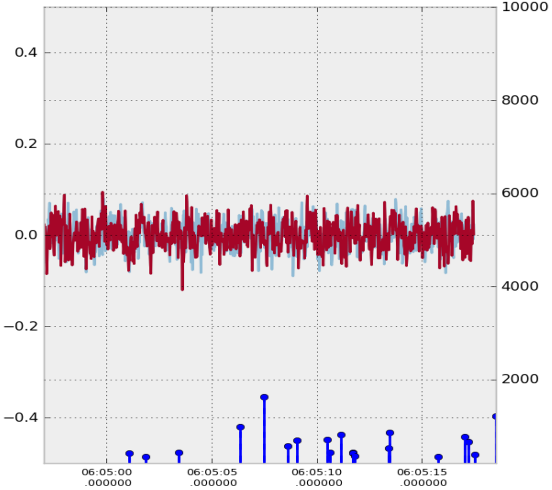


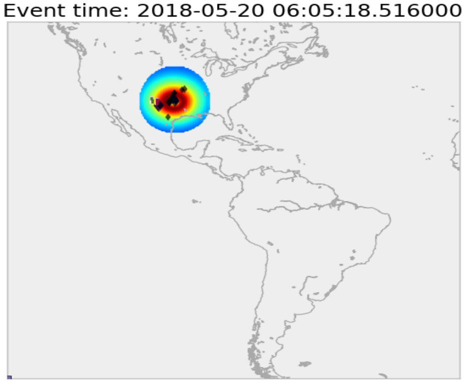
Thunderstorms in Oklahoma - 2018.05.20





Storms in Oklahoma - a sequence of 1-min data from a Swarm





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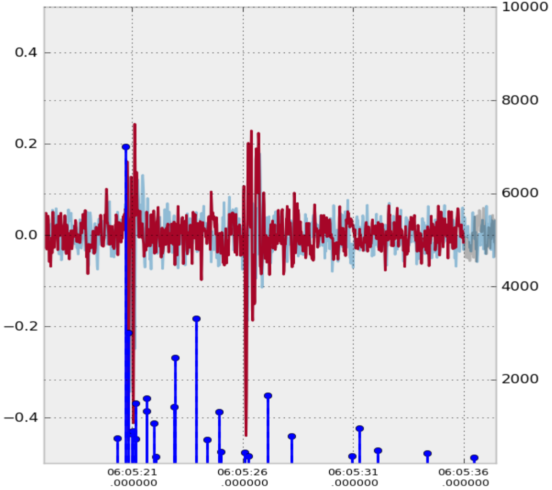

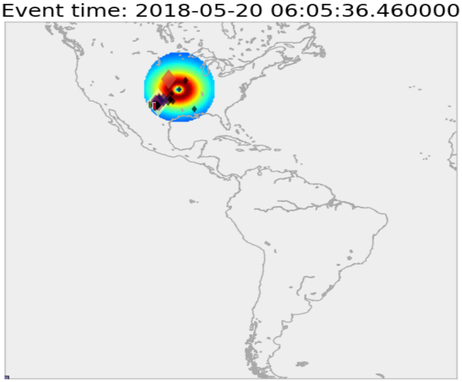

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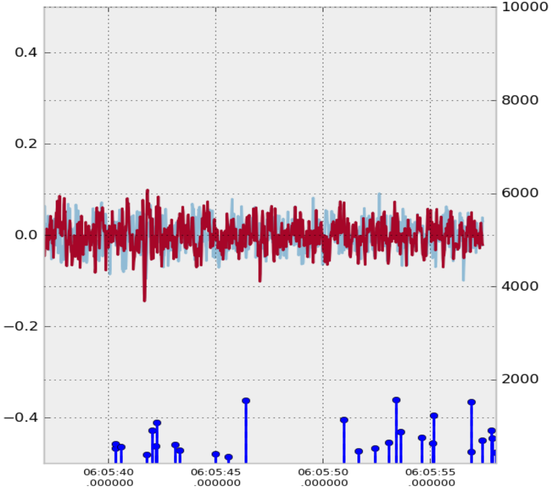
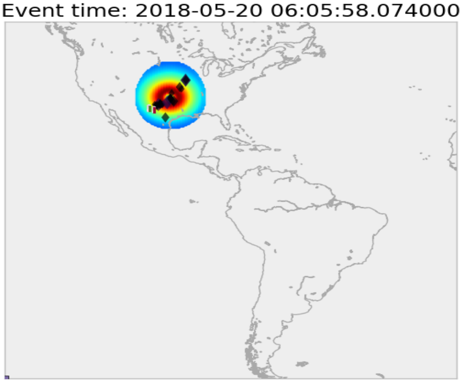




Storms in Oklahoma

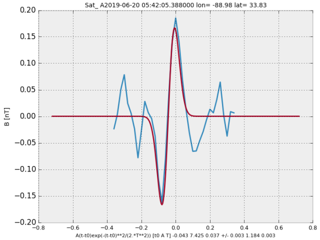
Double structure of peaks observed on Swarm Alpha and Charlie

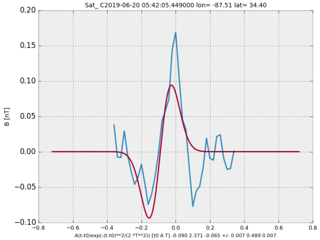
- During the sequence of 5 seconds: GLM registers following 4 strong flashes with energy of Record # 1: [7009.0, 144 ms] 20-May-2018 06:05:20.706
  Record # 2: [3010.0,162.0 ms] 20-May-2018 06:05:20.850
  Record # 12: [2474.0,644.0] 20-May-2018 06:05:22.926
  Record # 14: [3313.0,908.0] 20-May-2018 06:05:23.906
- peak Swarm A: T_1 = 06:05:20.888000 (Amp -0.221), T_2 = 06:05:26.227000 (-0.184), T_3 = 06:05:26.787000 (0.173)
- peaks - Swarm C: T_1= 06:05:21.065000 (-0.412) , T_2 = 06:05:21.125000 (0.248), T_3 = 06:05:26.165000 (-0.435), T_4 = 06:05:26.405000 (0.217)
- Time delay between the strongest flashes, and extreme peaks in both Swarm satellites, is not greater than 3 sec. which would suggest that Swarm passes in very close proximity of the storm and observed fluctuations suggest directly induced effect on magnetometers.

20-sec. sequence in the central part of the storm

Oklahoma

Oklahoma/ TXS - "Citizen science" vs. our algorithms





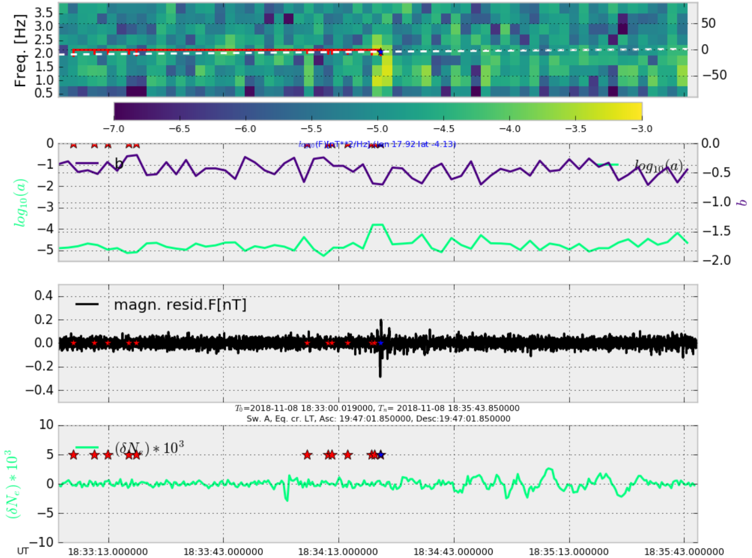
Plenty of daily updates with Jets:

https://twitter.com/paulmsmithphoto

Gulf of Mexico - One more case from US verified with the GLM

Gulf of Mexico

African thunderstorms - when we do not have the GLM data



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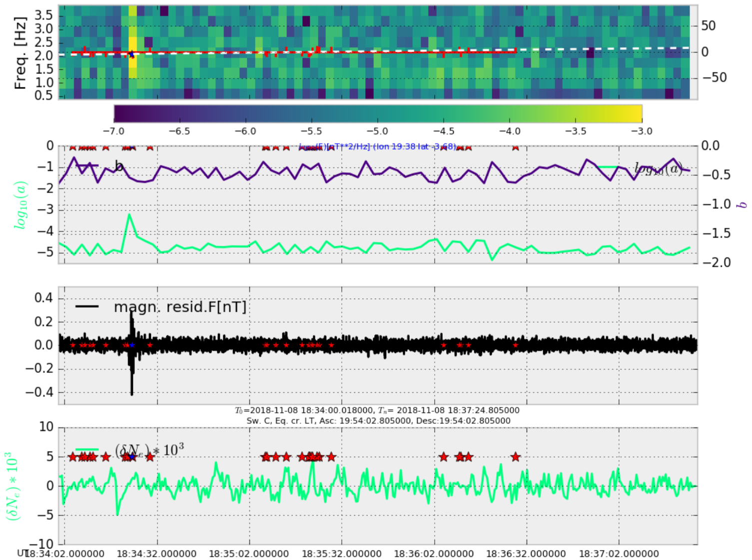
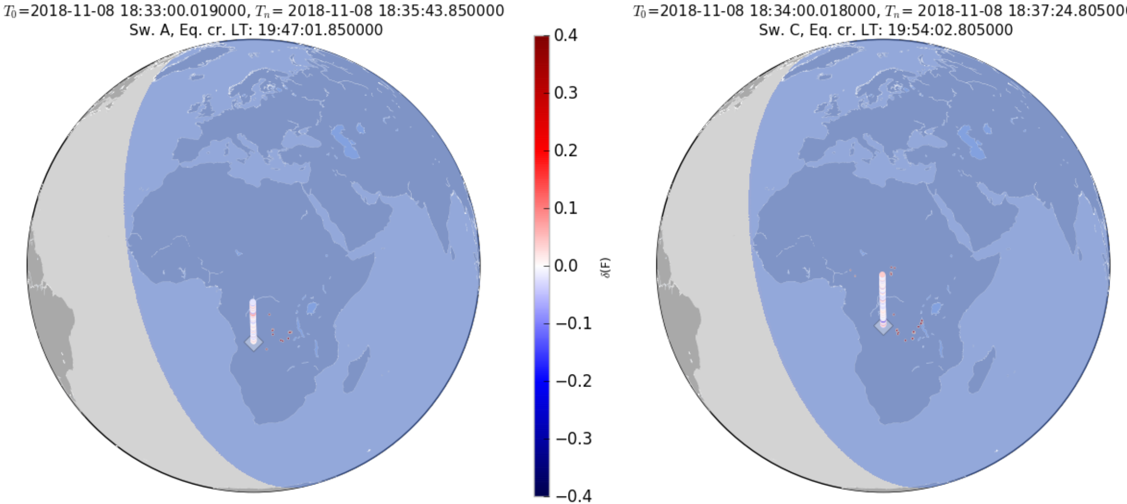
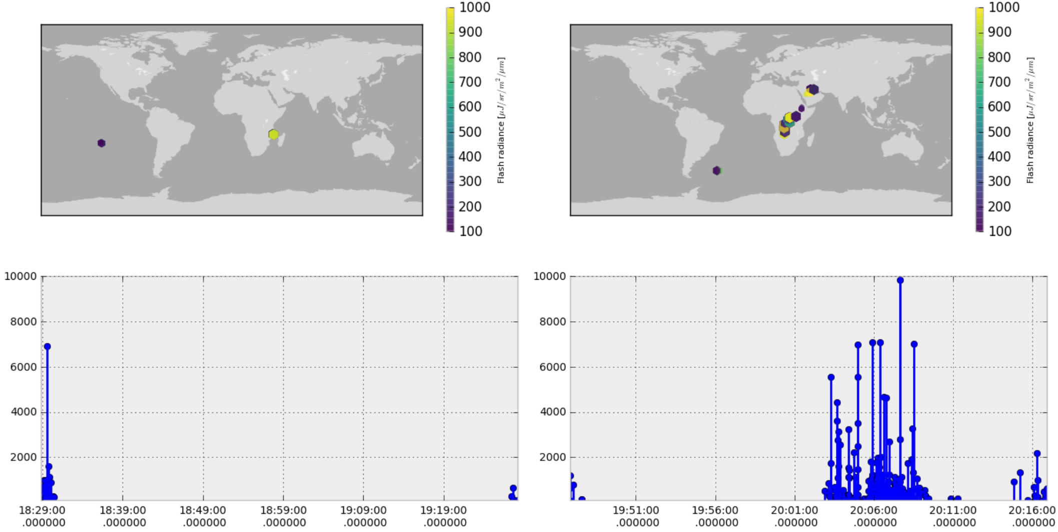


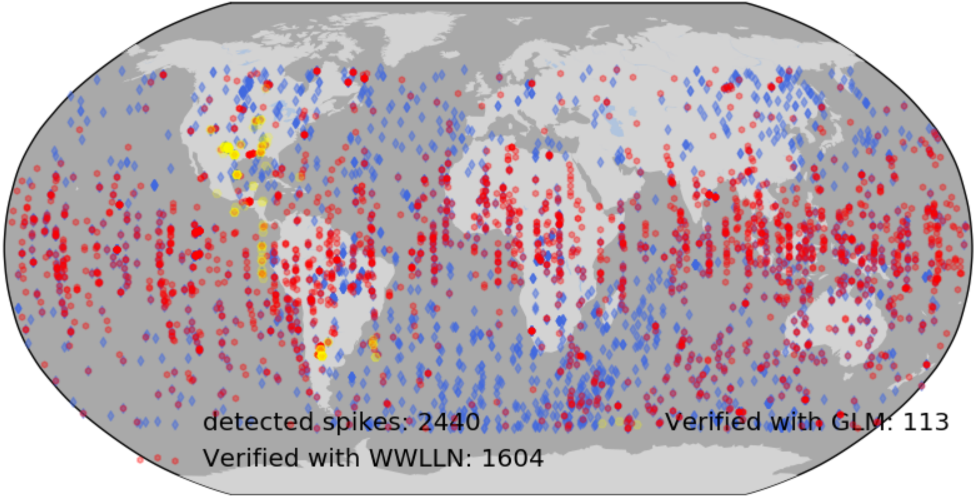
Thunderstorms in the African sector



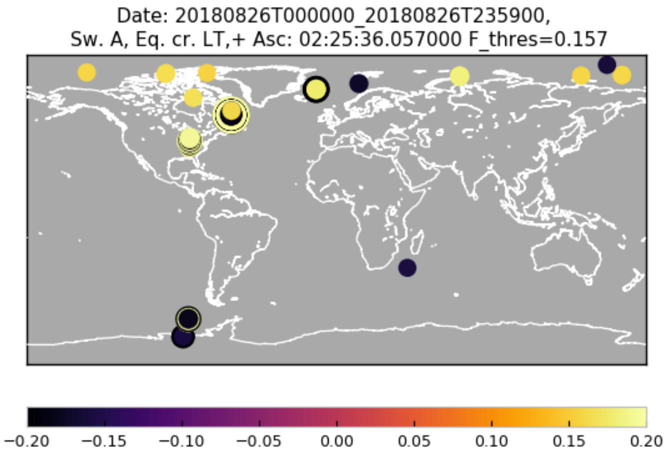
Thunderstorms in the African sector - LIS on ISS



Global distribution of detected events derived from Swarm

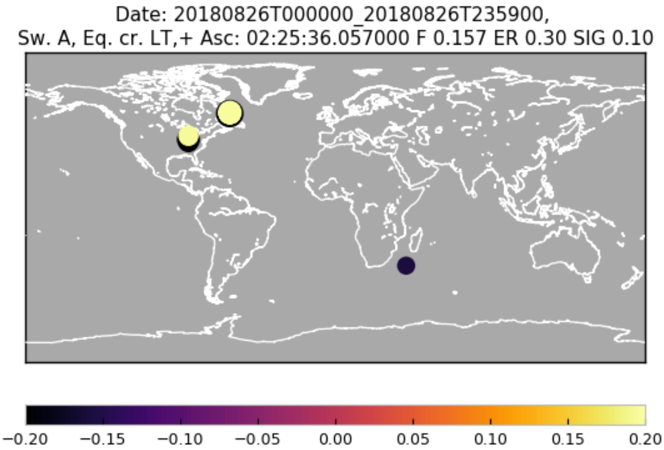


Are all detected spikes related to lightning activity?



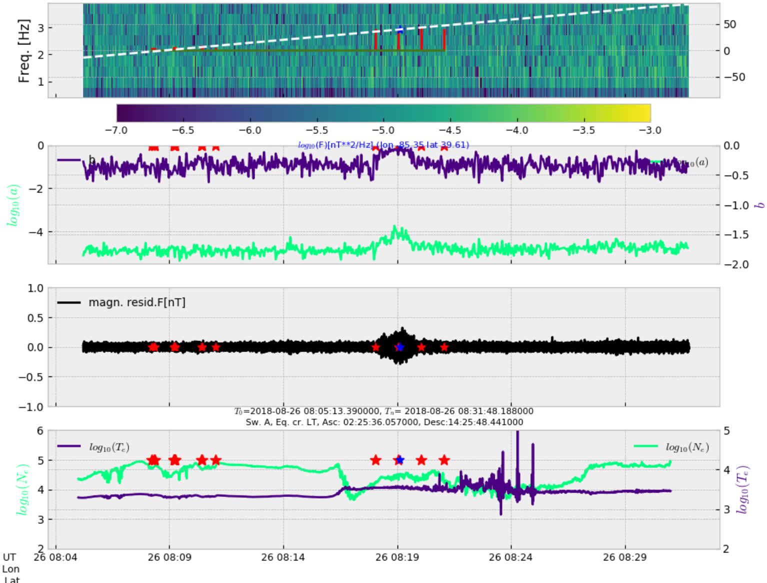
Nightside detection on a day with highly disturbed magnetic conditions

Are all detected spikes related to lightning activity?

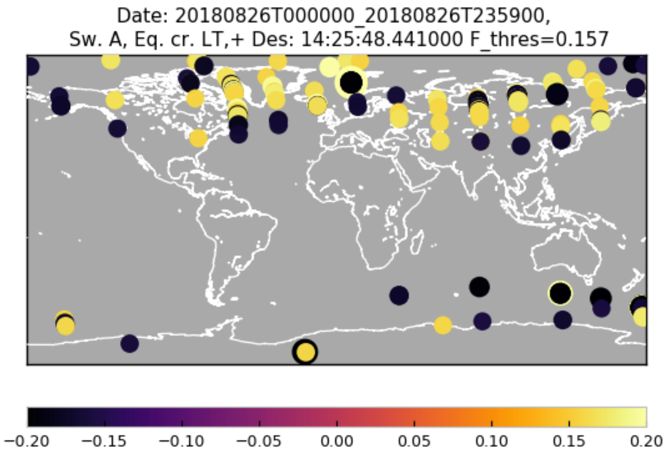


Nightside detection on a day with highly disturbed magnetic conditions

Sample spectrum

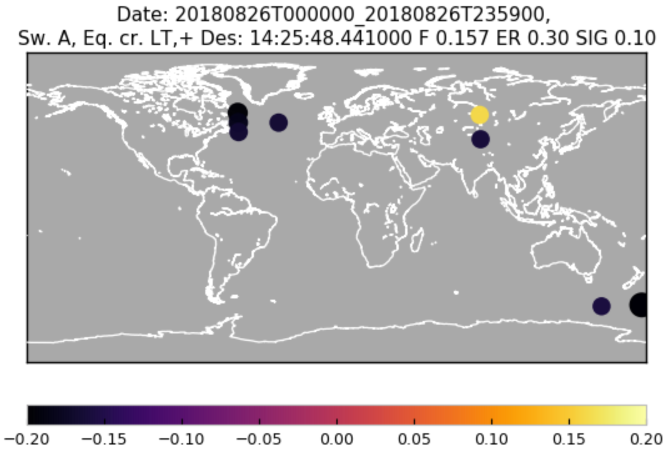


Are all detected spikes related to lightning activity?



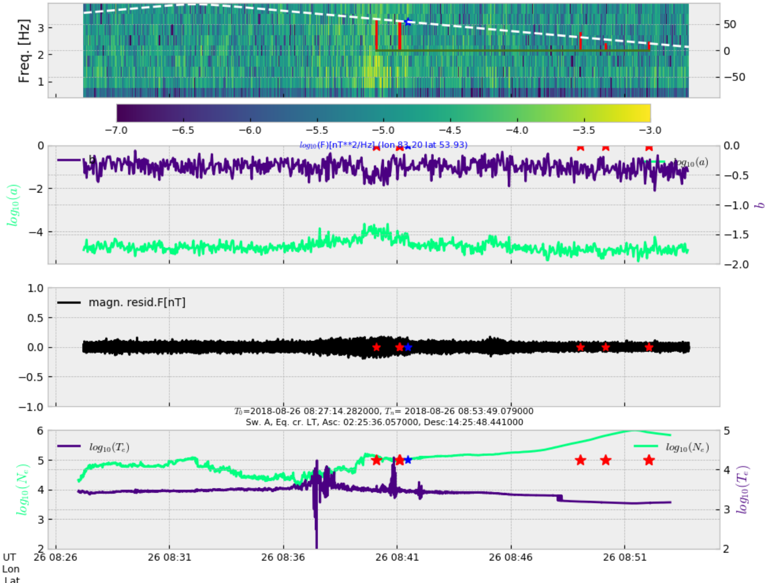
Dayside detection on a day with highly disturbed magnetic conditions

Are all detected spikes related to lightning activity?



Dayside detection on a day with highly disturbed magnetic conditions

Sample spectrum

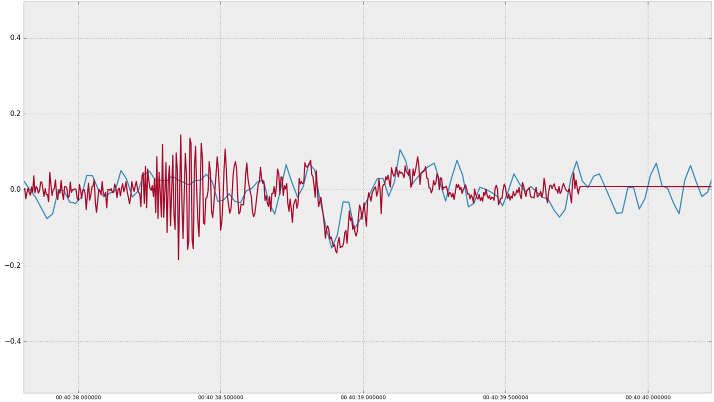


ASM 250 Hz vs. VFM 50 Hz

Pending question: Could we improve results using the ASM data?

Comparison between method used by Gauthier‘s (Hulot) group (red line) and our Team (blue line)

Agreement in general trend, due to sampling we do not see small scale structures.



Whistler type emission - triggered by relatively weak lightning event - we do not see any evidences of sharp peaks

Milestone achievements:

- Critical dataset providing a set of cases for the publication
- Database of analyses samples - from 2017 till current time, updated on daily basis: set of graphics documenting each case http://swarm4anom.cbk.waw.pl/gauss/
- original data (Swarm MAG and EFI data, merged into a single file and integrated with datasets representing events are stored

Summary

- **After more than 2 years..., we think that at least we know how to look at data to be successful in identification of TLEs**
- Joint analysis between Swarm and GLM confirms, that spikes with amplitudes higher than 0.1 nT, can be produced by TLEs
- Detection of 'regular' thunderstorms is harder, because signal is below assumed threshold, but
- Joint analysis with upcoming lightning imagers on board the MTG-I satellites, will improve observation in the European and African sector
- *MTG will see the launch of six new geostationary (imaging and sounding) satellites from 2021 onwards.*
- Scientific questions: Strong dumping of the signal - the amplitude of disturbances and distance from the source?