Experimental evidence of a link between lightning and magnetic field fluctuations in the upper ionosphere observed by Swarm

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ESA Swarm4Anom project
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Outline

Presenting the content of a paper submitted to GRL (currently under review) ...

… with some additional explanations

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Experimental Evidence of a Link Between Lightning and Magnetic Field Fluctuations in the Upper Ionosphere Observed by Swarm

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Key Points:

- Lightning can generate ULF fluctuations leaking into the upper ionosphere
- Observations show that the fluctuation amplitude is proportional to the lightning charge moment
- The ULF fluctuations generated by lightning can be detected by low-Earth orbit satellites, e.g., the Swarm constellation

Schematic view of joint Swarm-GLM-WERA observations

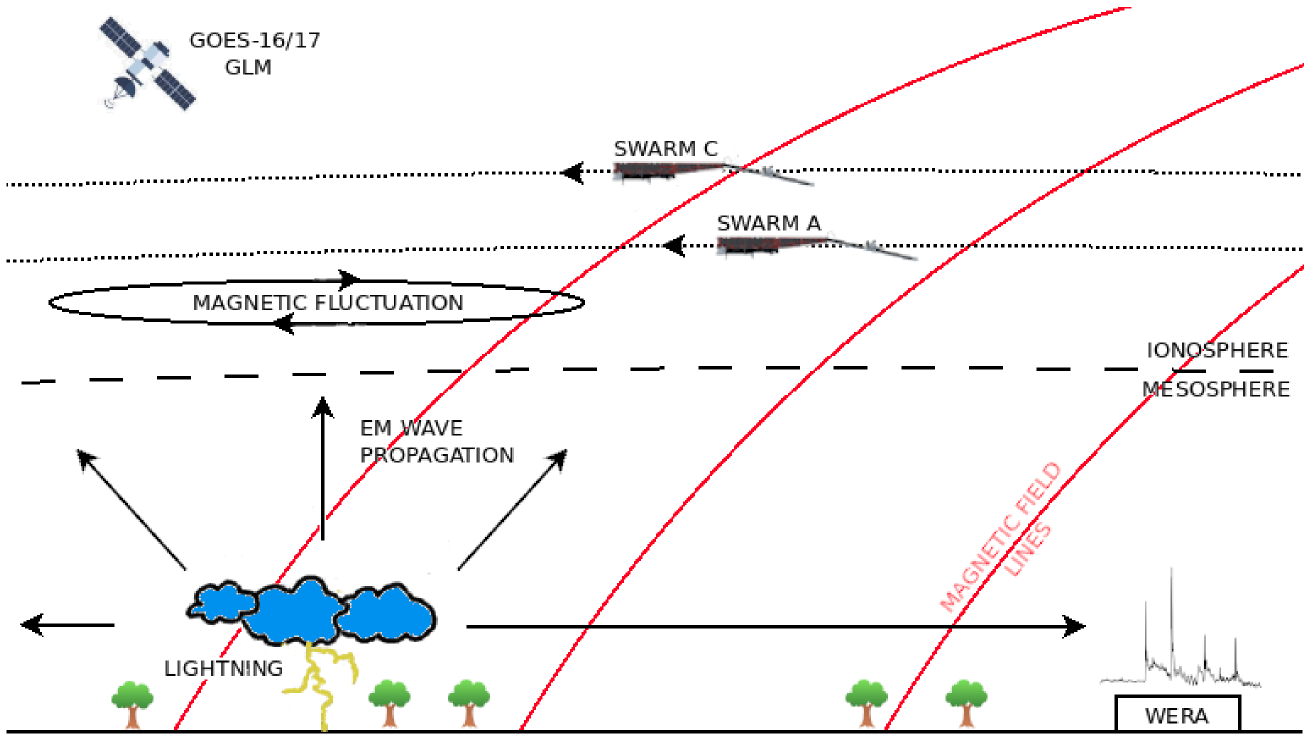
Lightning discharge generates EM wave

Theory: toroidal magnetic fluctuation (azimuthal MF in lightning-axis-centered cylindrical geometry)

Earth-ionosphere-waveguide propagation detected by WERA radiolocator

Conversion into plasma wave at ionosphere-mesosphere boundary, ionospheric waves detected by Swarm A and C

Top-of-clouds optical emission observed by GOES-16/17 GLM instrument



Not-to-scale picture: lightning discharges 2-3 km (-CG type) or 10-15 km (+CG type), the mesosphere-ionosphere boundary is at 100 km, the Swarm satellite orbit is at 440 km, while the GOES-16/17 geostationary orbit is located at 35700 km

Swarm VFM

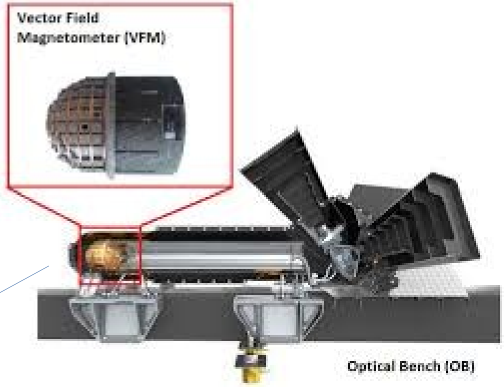
Swarm A and C satellites

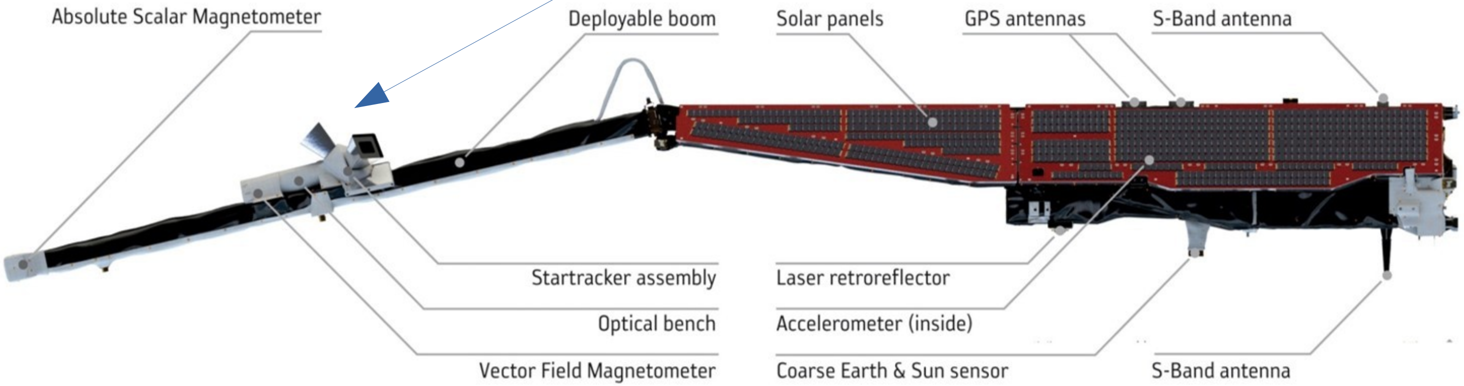
VFM instrument, originally in NEC frame

Measurements of the magnetic field vector in the upper ionosphere

Sampling rate 50 Hz

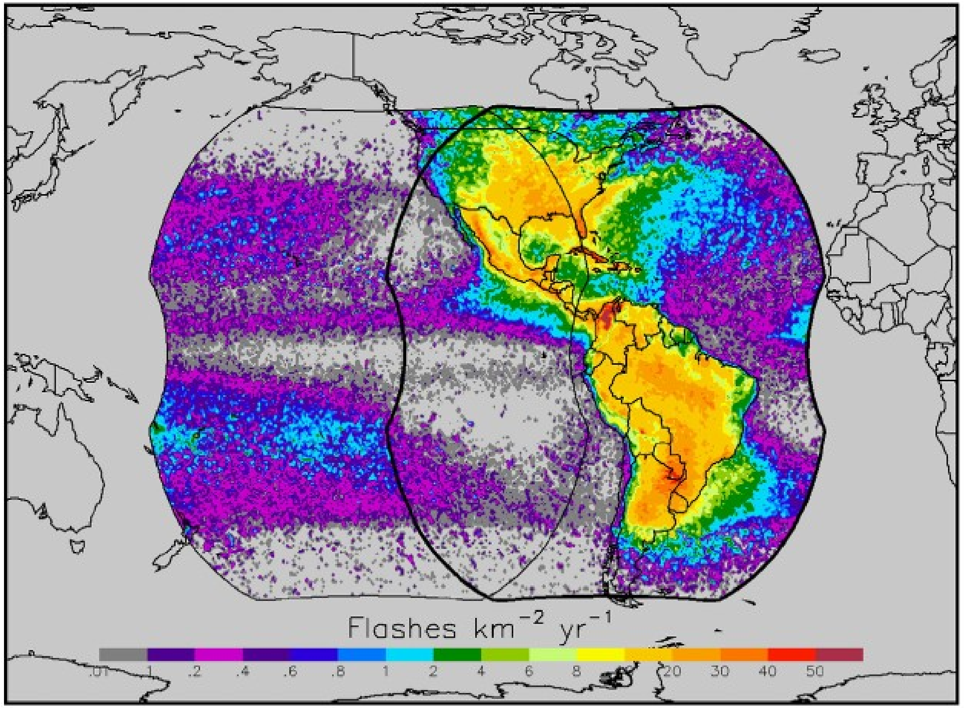
Altitude 440-450 km





GOES-16/17 (R series) GLM

Goodman et al. 2013



field of view of GOES-16/17 GLM instrument: North and South America, adjacent oceanic regions

Geostationary Lightning Mapper: observations of top-of-clouds optical emission associated with lightning flashes

GLM is mapping the total lightning activity during day (more difficult) and night

pixel FOV (nadir): 8 km
pixel FOV (corner): 14 km

wavelength: 777.4 nm (oxygen line)

frame rate: 2 ms

WERA radiolocator (see Janusz's presentation)

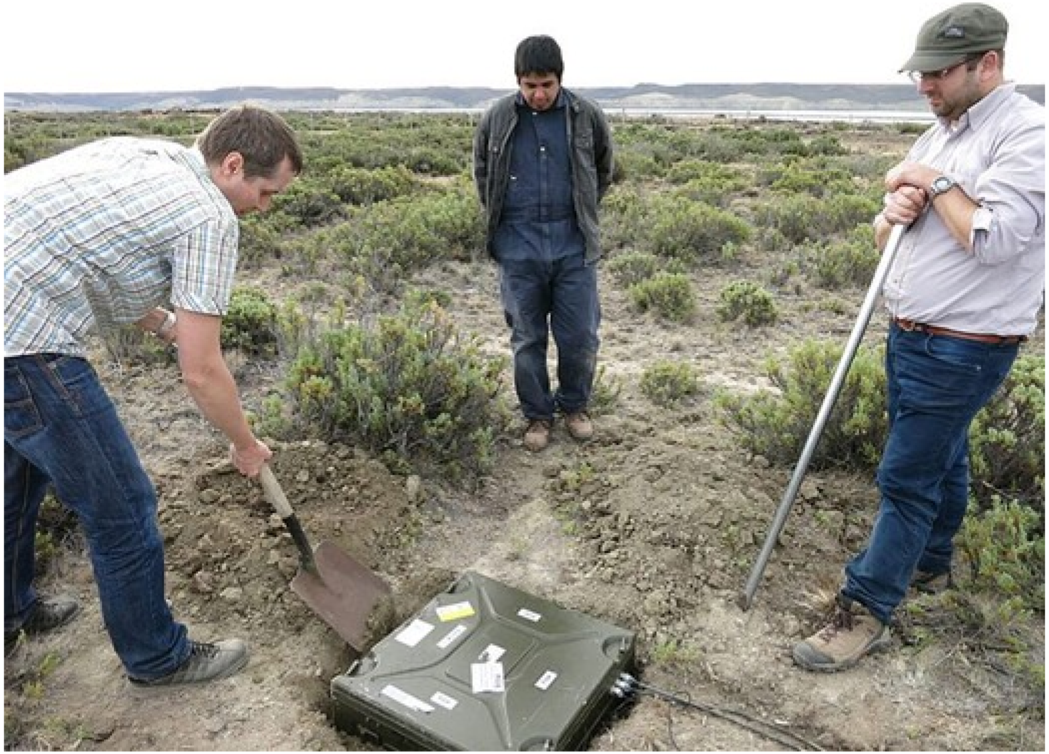
World ELF Radiolocation Array

Ground-based ELF receivers equipped with magnetic antennas

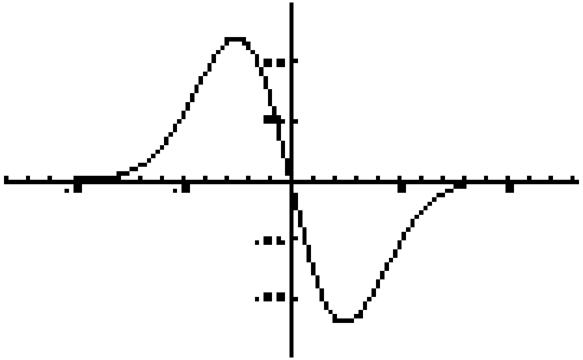
Measurements of the activity of waves propagating in the Earth-ionosphere waveguide

Frequency range: from 0.03 to 300 Hz

Three stations: Hylaty (Poland), Hugo (Colorado, USA), Patagonia (Argentina) make it possible to estimate the location and strength of lightning events



Data selection procedure (see also Ewa's presentation)



Based on fluctuations in the magnetic field strength

Detrending by fourth-order-polynomial fitting

Searching for time intervals with good matching to
a predefined signature (the derivative
of a Gaussian function, time scales between 0.1 and 0.5 s)

Searching for events localized closely (less than 5 deg) to lightning events, based on public-access World Wide Lightning Location Network (WWLLN) data

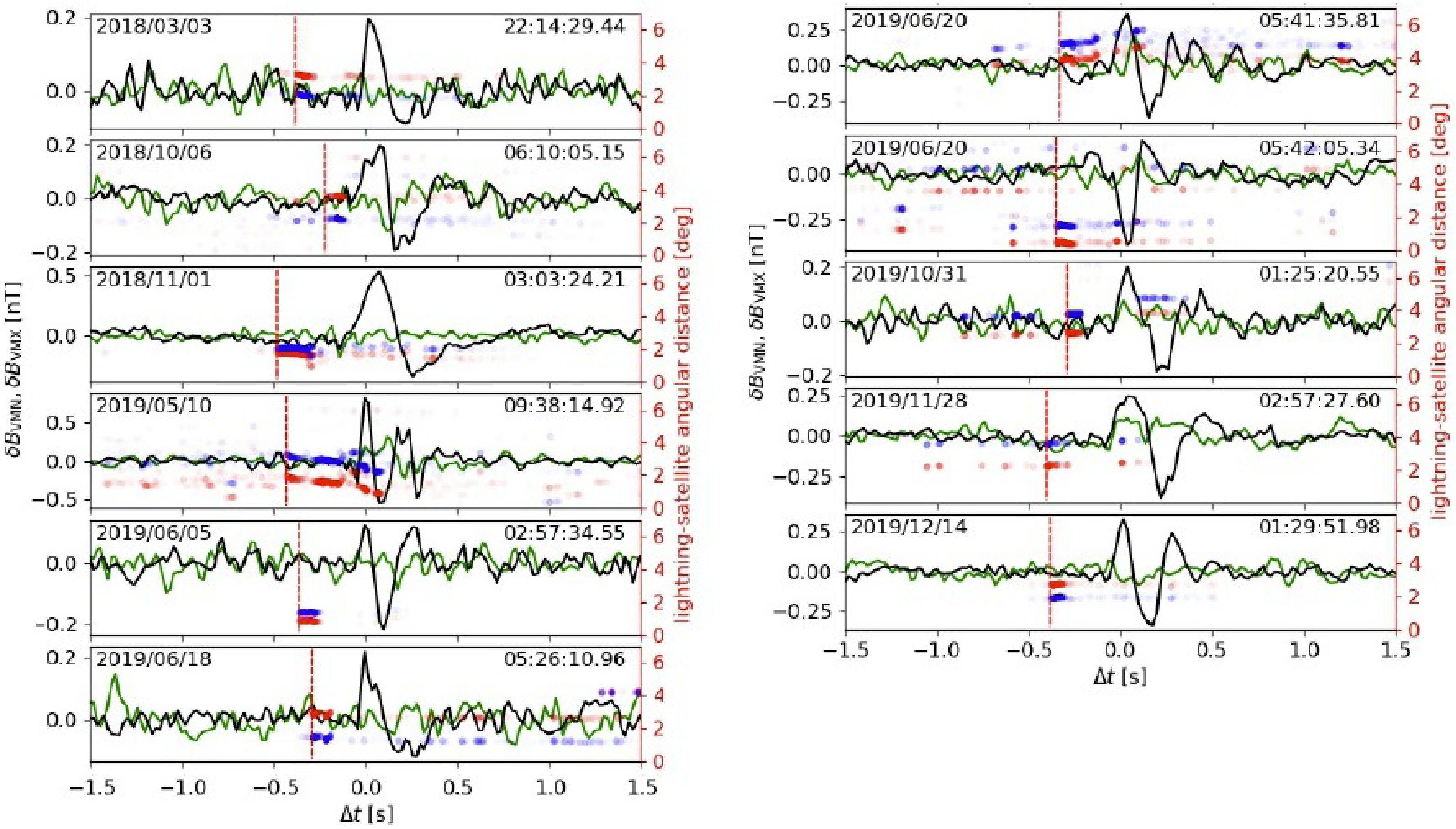
Events observed by both Swarm A and C (crucial for inter-satellite cross-correlation analysis)

Events of isolated-impulse type clearly standing out from surrounding noise

GLM data availability (detailed information on the time, location, optical energy and spatial extent of flashes)

11 cases found between March 2018 and December 2019 using the selection criteria

Swarm A vs GLM data



Time-distance-energy plots for lightning events

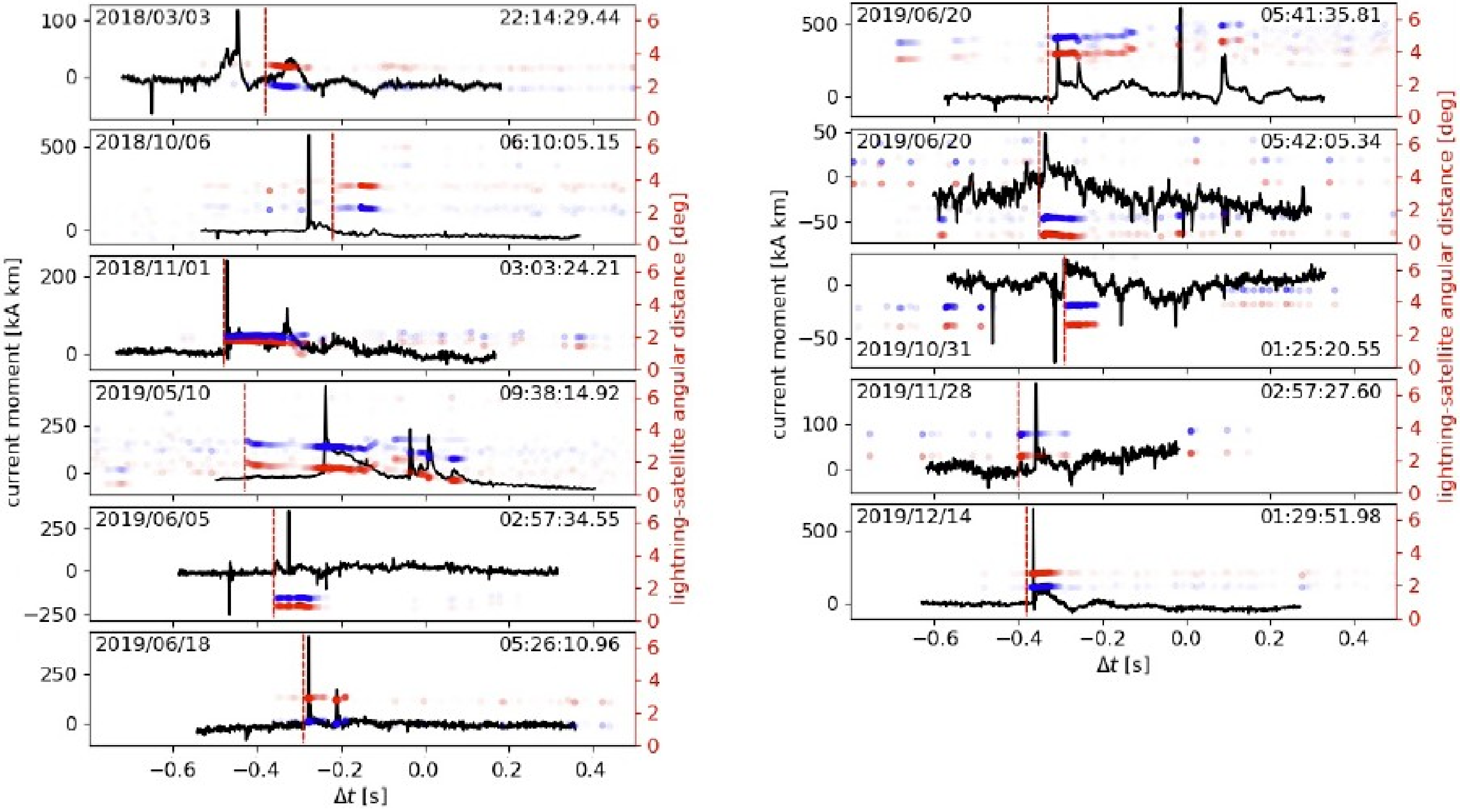
Red (SwA) and blue (SwC) stripes show lightning events

VFM maximum (black) and minimum (green) variance components are shown

Time lags typically 0.2-0.5 s

Peak-to-peak amplitude: 0.3-1.3 nT (max var)

GLM vs WERA data



- Time-distance-energy plots for GLM (as in previous slide)
- WERA-based current moment (black line)
- Typically optical emission is shortly followed by peak in WERA waveform (return stroke)
- Continuing current on a longer timescale
- Two sources of information on lightning events

Geometry of magnetic fluctuation generated by a lightning discharge

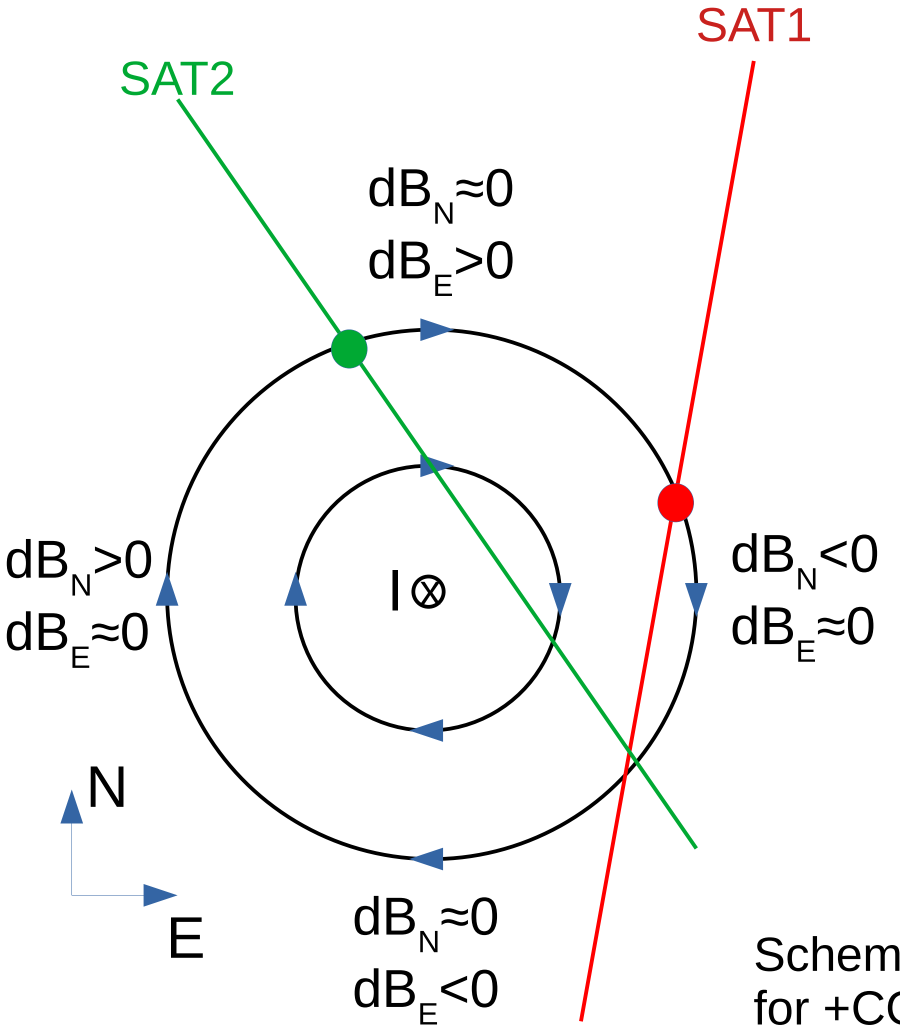
Direction of MF of fluctuation in different locations around a discharge, leading disturbance in bipolar waveform

View from the top, discharge represented by a current I along an axis perpendicular to the slide

Fluctuation dominant component is azimuthal in lightning-axis-centered cylindrical geometry [Mazur et al. (2018)]

Direction of the fluctuating field depends on satellite position wrt the discharge

Caveat: interpretation in terms of variations of NE components valid only for low- and mid-latitudes



Scheme for +CG discharge

Geo locations

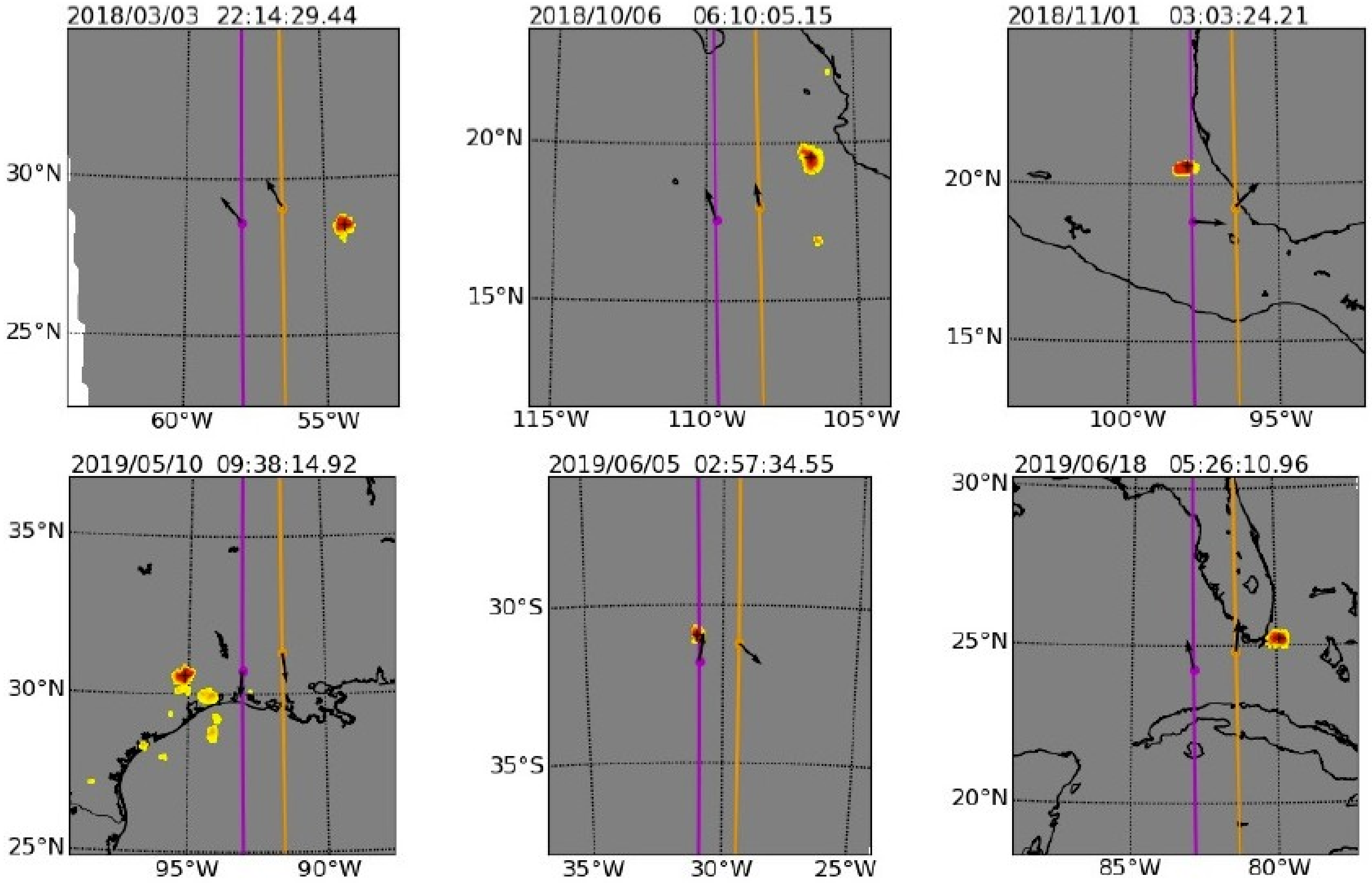
Swarm A (magenta) and C (orange)

GLM events: all (yellow), brightest (red)

VFM max var direction – black arrows

Toroidal MF fluctuation, +CG (clock-wise)

Local nighttime



Geo locations cont’d

Swarm A (magenta) and C (orange)

GLM events: all (yellow), brightest (red)

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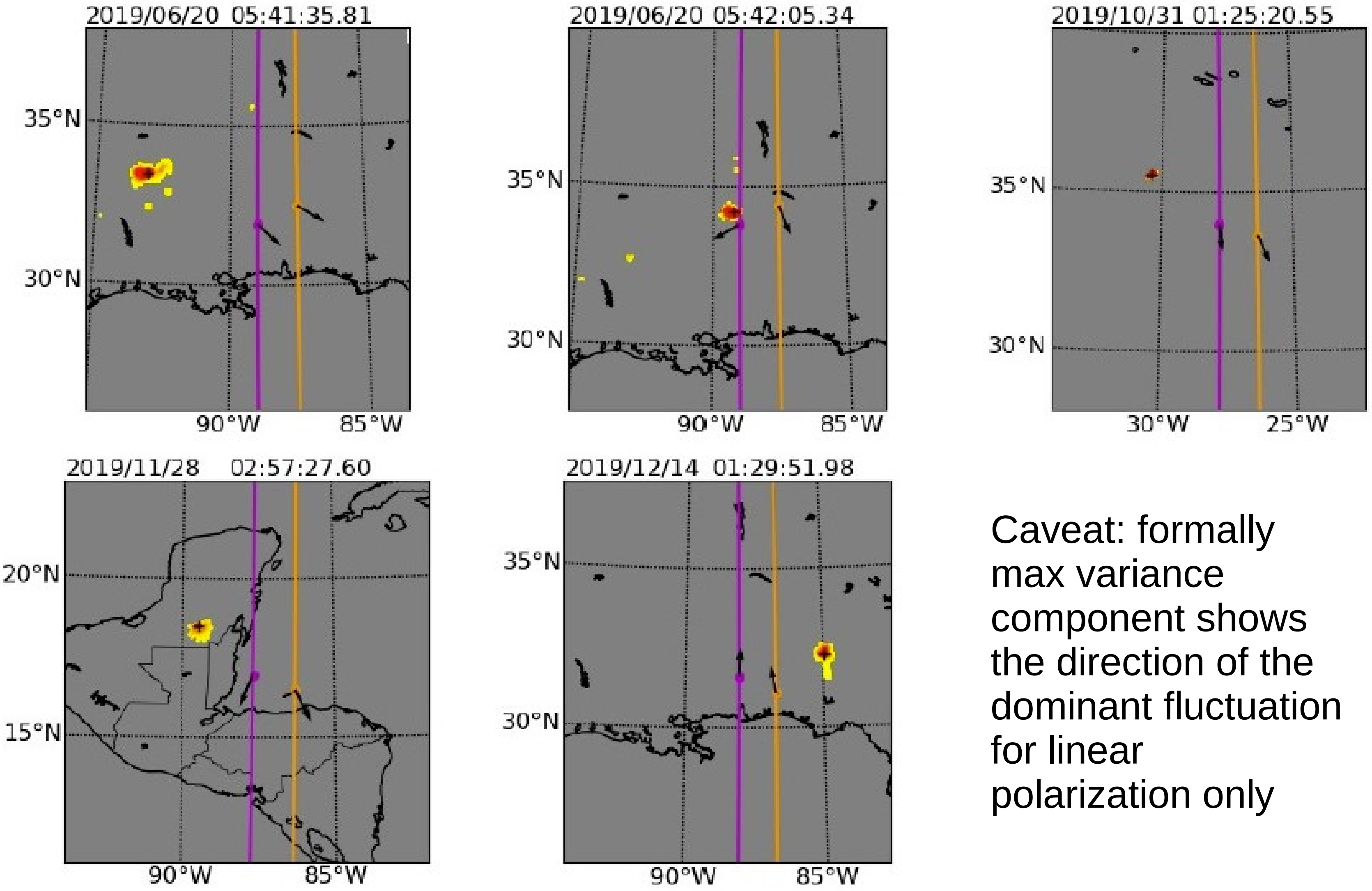
Toroidal MF fluctuation, +CG (clockwise)

Local nighttime



Caveat: formally max variance component shows the direction of the dominant fluctuation for linear polarization only

Fluctuation amplitude vs. lightning charge moment

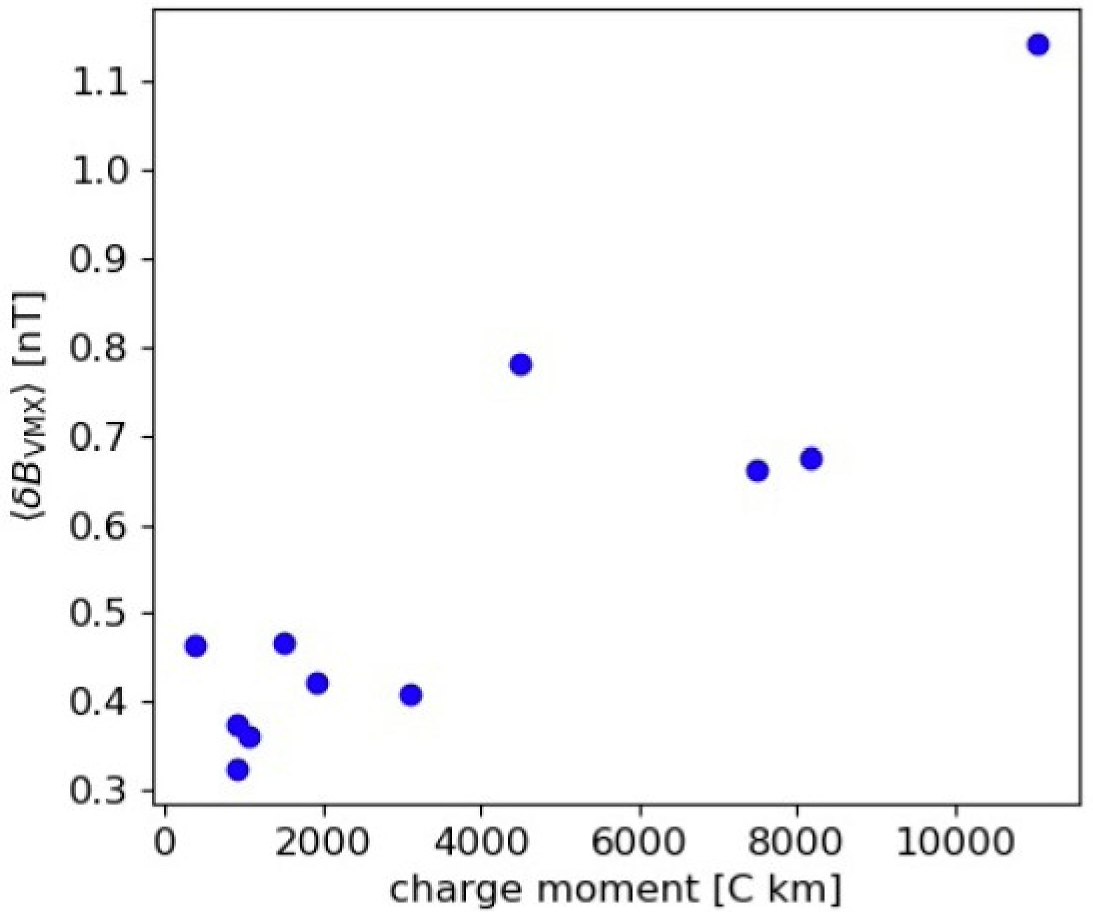
Fluctuation amplitude <δB_{VMX}> of the max variance component averaged over Swarm A and C measurements

Charge moment characterizes the strength of a discharge estimated from WERA measurements by integration in time of the current moment

Clear dependence suggests a real causality relationship

Significant scatter present

Linear approximation would lead to nonzero vertical axis intercept



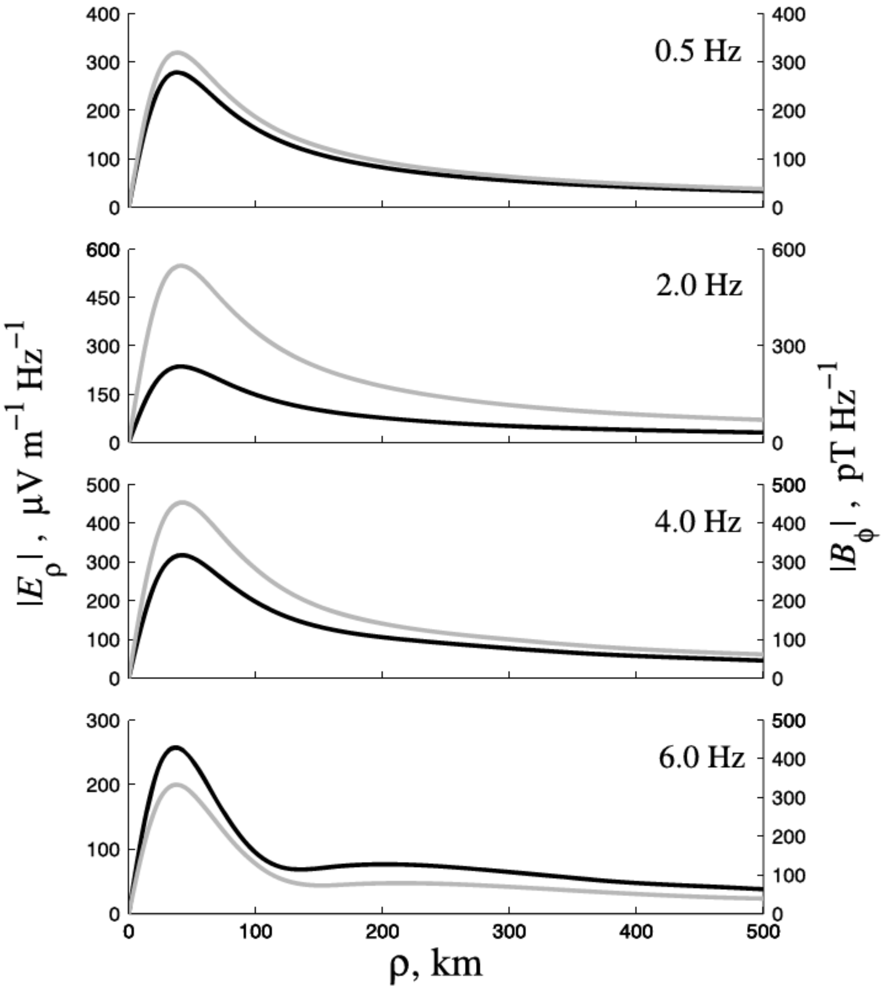
Reason for scatter in amplitude vs. charge-moment dependence

Theory: fluctuation amplitude is significantly modulated by the distance ρ between a discharge and a probe

Using <δB_{VMX}> we do not account for the modulation, which results in the scatter seen in the previous slide

Other factors possibly responsible for the scatter: ionospheric inhomogeneities

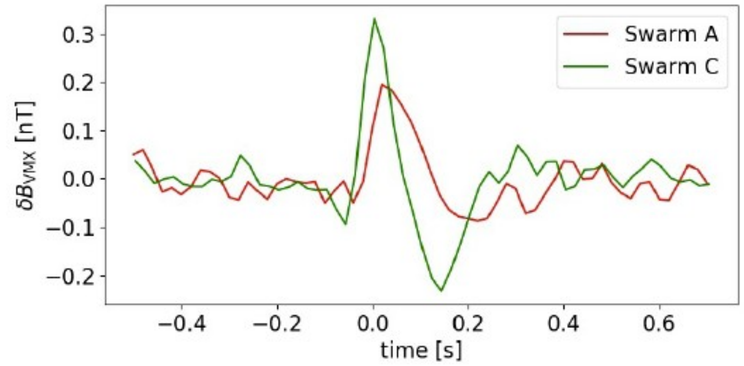
Mazur et al. (2018)



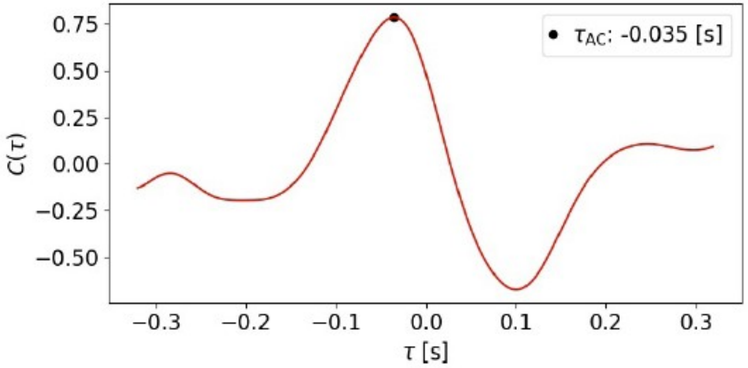
Finding time lag between Swarm A and C observations

Lag-dependent cross-correlation coefficient

$$C(\tau) = \frac{\left\langle \left[\delta B^{\mathrm{A}}_{\mathrm{VMX}}(t) - \langle \delta B^{\mathrm{A}}_{\mathrm{VMX}}(t)\rangle\right]\left[\delta B^{\mathrm{C}}_{\mathrm{VMX}}(t+\tau) - \langle \delta B^{\mathrm{C}}_{\mathrm{VMX}}(t+\tau)\rangle\right]\right\rangle}{\sqrt{\langle[\delta B^{\mathrm{A}}_{\mathrm{VMX}}(t)]^2\rangle - \langle \delta B^{\mathrm{A}}_{\mathrm{VMX}}(t)\rangle^2}\sqrt{\langle[\delta B^{\mathrm{C}}_{\mathrm{VMX}}(t+\tau)]^2\rangle - \langle \delta B^{\mathrm{C}}_{\mathrm{VMX}}(t+\tau)\rangle^2}}$$



Global maximum of the cross-correlation function C(τ) may serve as an indicator of an average inter-satellite time-lag τ_{AC}



Prior to computations of C(τ), we interpolate linearly the original data onto a finer time grid. Therefore, formally we can determine τ_{AC} with resolution 0.001 s.

Distance-lag relationship

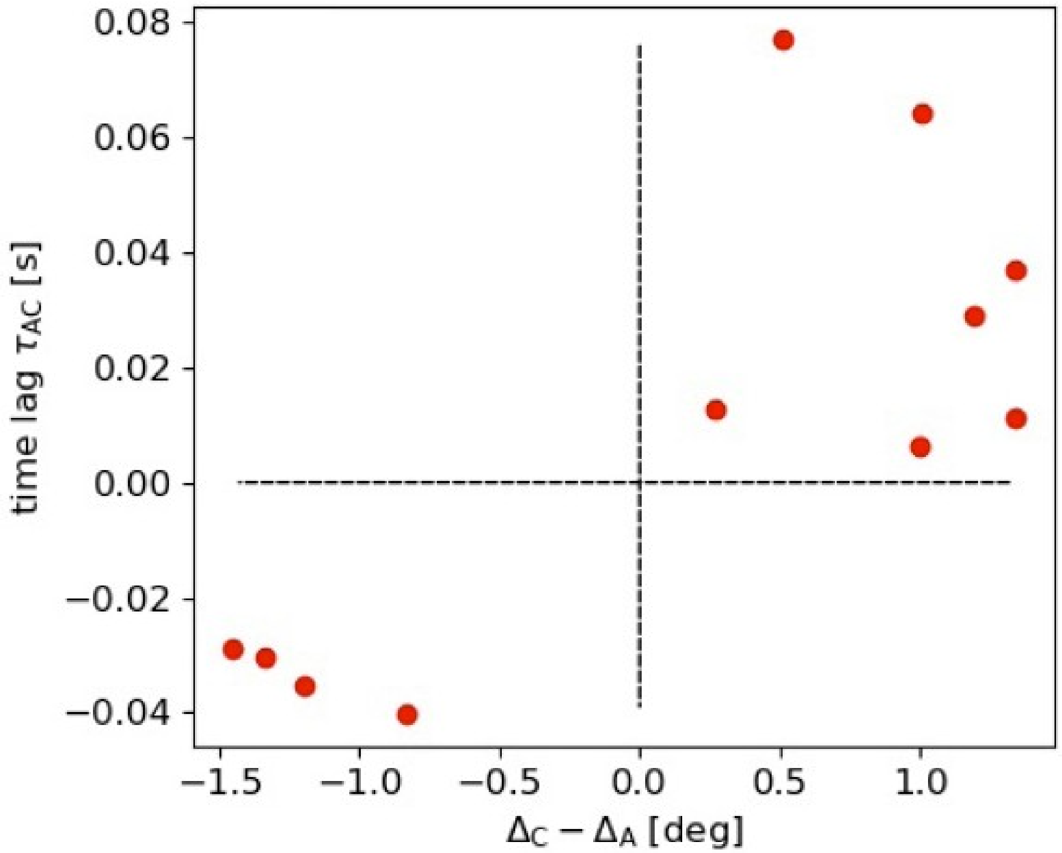
Propagation of a wave disturbance implies usually a distance-lag relation

Detection by SwA before SwC corresponds to time lag $\tau_{AC}>0$ (by definition of τ_{AC})

$\Delta_C-\Delta_A>0$ means that SwA is closer, so it should detect fluctuation before SwC, thus $\tau_{AC}>0$

The expected arrangement in $\Delta_C-\Delta_A$ vs. τ_{AC} plot is confirmed by observations

Significant scatter present



Reasons for scatter in distance-lag relationship

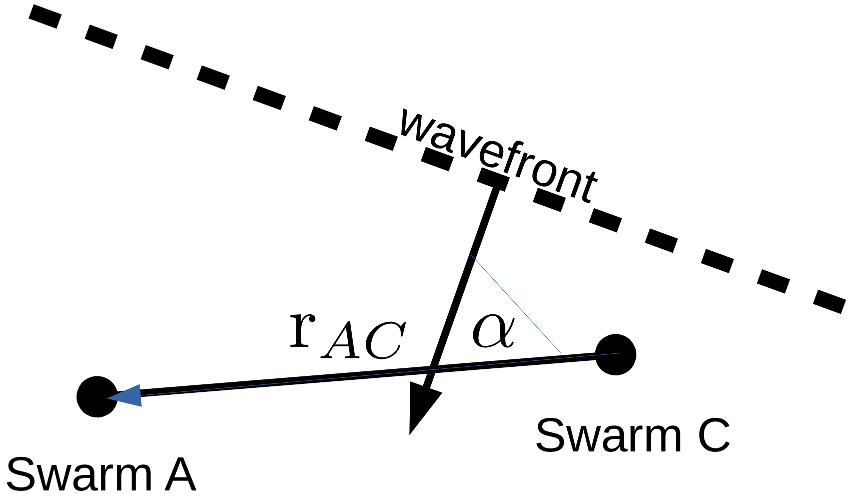
Factors affecting distance-lag relation:

- wave propagation speed V_W
- angle α between normal to the wavefront and inter-satellite vector

Variations of wave propagation speed can be expected to be significant for the considered cases due to:

- variations of density and relative concentration of different ion species in the ionosphere
- variations of Earth's main magnetic field strength with geographic location

Relative orientation of the wavefront and inter-satellite vector depends on satellite location wrt lightning discharge



$$V_W = \left| \cos\alpha \frac{|\mathbf{r}_{AC}|}{\Delta t} \right|$$

Variations of V_W and α are not accounted for in the previous slide, thus they can be expected to generate random scatter

Swarm-related summary

No.	Date	Time t_0	Swarm A loci	Swarm C loci	δB_{A} [nT]	δB_{C} [nT]	τ_{AC} [s]
1	2018/03/03	22:14:29.44	28.65° N 57.99° W	29.13° N 56.53° W	0.28	0.56	-0.035
2	2018/10/06	06:10:05.15	17.56° N 109.69° W	17.98° N 108.24° W	0.39	0.43	-0.030
3	2018/11/01	03:03:24.21	18.85° N 97.90° W	19.29° N 96.44° W	0.88	0.45	0.013
4	2019/05/10	09:38:14.92	30.78° N 93.04° W	31.35° N 91.57° W	1.34	0.94	0.011
5	2019/06/05	02:57:34.55	31.79° S 30.86° W	31.23° S 29.39° W	0.34	0.41	0.077
6	2019/06/18	05:26:10.96	24.26° N 82.87° W	24.82° N 81.41° W	0.34	0.39	-0.029
7	2019/06/20	05:41:35.81	31.94° N 88.99° W	32.50° N 87.51° W	0.73	0.62	0.006
8	2019/06/20	05:42:05.34	33.84° N 88.98° W	34.40° N 87.51° W	0.58	0.35	0.064
9	2019/10/31	01:25:20.55	34.03° N 27.79° W	33.68° N 26.35° W	0.39	0.26	0.029
10	2019/11/28	02:57:27.60	16.99° N 87.69° W	16.53° N 86.30° W	0.63	0.30	0.037
11	2019/12/14	01:29:51.98	31.63° N 88.10° W	31.12° N 86.75° W	0.66	0.90	-0.040

GLM and WERA-related summary

No.	$t_{\mathrm{GLM}} - t_0$ [s]	GLM max loci	Δ_{A}	Δ_{C}	M_{Q} [C km]
1	-0.38	28.54° N 54.33° W	3.22°	2.02°	1910
2	-0.22	19.53° N 106.50° W	3.61°	2.27°	3100
3	-0.48	20.59° N 98.09° W	1.75°	2.02°	7490
4	-0.43	30.58° N 95.19° W	1.86°	3.20°	11040
5	-0.36	30.94° S 30.95° W	0.85°	1.36°	900
6	-0.29	25.25° N 79.90° W	2.88°	1.43°	1060
7	-0.33	33.47° N 93.10° W	3.79°	4.79°	8190
8	-0.35	34.20° N 89.21° W	0.41°	1.42°	375
9	-0.29	35.52° N 30.39° W	2.61°	3.80°	900
10	-0.40	18.49° N 89.48° W	2.28°	3.62°	1500
11	-0.38	32.27° N 84.96° W	2.74°	1.91°	4500

Conclusions

11 observations of isolated-impulse magnetic fluctuations by Swarm can be linked to lightning events based on proximity in space and time

The spatio-temporal correlation is confirmed by clear relations between lightning and fluctuation properties. One relation connects the fluctuation amplitude with charge moment of lightning. Another one links the time lag between Swarm A and C observations with the distance between the satellites and lightning. The relations suggest a real causality relationship.

The cases demonstrate a leakage of electromagnetic fluctuations caused by lightning events into the upper ionosphere. To our knowledge this is the first direct experimental confirmation in the ULF range.

All analyzed cases were observed during nighttime and in low-latitude regions

Time delay between the lightning occurrence and the satellite detection is 0.2-0.5 s, generally consistent with theoretical predictions by Mazur et al. (2018). The delay suggests an average propagation speed in the ionosphere 600-2000 km/s, comparable to the Alfven speed.

Conclusions cont'd

The delays suggest that we observe effects of direct propagation of lightning-generated disturbance rather than effects of excitation of the IAR resonance

Typical magnitude of the observed lightning-related magnetic perturbations is 0.3-1.3 nT (peak-to-peak), which is significantly smaller than 4 nT resulting from modeling by Mazur et al. (2018)

Lightning-satellite geographic distance should be less than 5° for detection with Swarm VFM

Swarm VFM instrument is dedicated to measure the Earth's main magnetic field, which is much stronger (typically 25-65 μT) than the amplitude of the fluctuations under investigation. Therefore only strong lightnings located closely to Swarm are able to generate spikes exceeding the VFM-instrument noise level. A dedicated instrument for the fluctuations could provide a significantly larger statistical sample for analysis.

Vector magnetometer technique provides some additional information as compared to scalar measurements. This additional information can be useful for comparison with models and wave diagnostic purposes.

Conclusions cont'd

Time lag between lightning occurrence and satellite detection is comparable to the wave period (or typical impulse time scale). Also the lightning-satellite distance is comparable to the wavelength (or typical impulse length scale). Therefore, we can say that the probe is close to the wave source. It is possible that we observe the process of wave generation rather that propagation of a well-formed wave.

We generally use public-access WWLLN data of inferior quality as compared to data available by subscription. Access to the full WWLLN database would presumably provide more cases for analysis.

Our results shed light on mechanisms of conversion of lower-atmospheric electromagnetic waves into ionospheric plasma waves and propagation of ionospheric waves between mesosphere-ionosphere boundary and the upper ionosphere. This can be useful for various diagnostic purposes.