Multi-Spacecraft Analysis of Dipolarization Fronts and Associated Whistler-Wave Emissions using MMS Data

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Key Points.

Magnetotail, Bursty Bluk Flows, Whistler Waves

Dipolarization fronts (DFs), embedded in bursty bulk flows (BBFs), play a crucial role in Earth's plasmasheet dynamics because the energy input from the solar wind is partly dissipated in their vicinity. This dissipation is in the form of strong low-frequency waves that can heat and accelerate energetic electrons up to the high latitude plasmasheet. However, the dynamics of DF propagation and associated low-frequency waves in the magnetotail are still under debate due to instrumental limitations and spacecraft separation distances. In May 2015 the Magnetospheric Multiscale (MMS) mission was in a string-of-pearls configuration with an average inter-satellite distance of 160 km, which allows us to study in detail the microphysics of DFs. Thus in this letter we employ MMS data to investigate the

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properties of dipolarization fronts propagating earthward and associated whistler-mode wave emissions. We show that the spatial dynamics of DFs are below the ion gyroradius scale in this region (∼500 km), which can modify the dynamics of energetic ions ahead of the DF (e.g. making their motion non-adiabatic). We also show that whistler-wave dynamics have a temporal scale of the order of the ion gyroperiod (a few seconds), indicating that the perpendicular temperature anisotropy can vary on such time scales.

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1. Introduction

Transient fast flows of plasma are often observed for a large range of geocentric distances in Earth's magnetotail, from −5 to about −30 Earth radii [*Ohtani et al.*, 2004]. They are thought to be formed by reconnection of stretched field lines in the tail [*Runov et al.*, 2009; *Sitnov et al.*, 2009] and/or in interchange heads [*Pritchett and Coroniti*, 2011, 2013]. These bursty bulk flows (BBFs) are well correlated with substorm activity [see, e.g., *Juusola et al.*, 2011] and are an important mechanism of the flux transport in the tail [*Baumjohann*, 1993; *Baumjohann et al.*, 2002; *Volwerk et al.*, 2008]. BBFs propagating Earthward are associated with the dipolarization of the stretched magnetic field line [see e.g., *Nakamura et al.*, 2002; *Runov et al.*, 2011, 2012], also called dipolarization front (DF), that is embedded in these flows and separates the hot, tenuous high-speed flow from the cold, dense and slowly convecting surrounding plasma. The typical scale of DFs in the near-Earth magnetotail is of the order of the ion inertial length and Larmor radius [see e.g. *Runov et al.*, 2011; *Fu et al.*, 2012a].

DFs are invariably associated with intense and broadband electromagnetic fluctuations, from the ion cyclotron frequency to larger than the electron cyclotron frequency [see *Zhou et al.*, 2009; *Khotyaintsev et al.*, 2011; *Huang et al.*, 2012; *Huang et al.*, 2015a; *Viberg et al.*, 2014, and references therein]. Various wave modes have been identified, such as lower-hybrid (LH) and whistler-mode waves. While LH waves are observed directly at the DFs, whistler waves are generally detected in the flux pile-up region (FPR), i.e. behind the DFs [*Khotyaintsev et al.*, 2011; *Deng et al.*, 2010; *Fu et al.*, 2014; *Li et al.*, 2015]. These

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waves, that are continually radiated outward from the BBFs to the auroral oval, are found to be a very efficient plasma sheet energy loss process [*Chaston et al.*, 2012; *Ergun et al.*, 2015], transferring the energy from the fields to the plasma [*Huang et al.*, 2015b; *Angelopoulos et al.*, 2013]. Whistlers have been previously recorded onboard Cluster [*Khotyaintsev et al.*, 2011; *Huang et al.*, 2012] and THEMIS [*Le Contel et al.*, 2009; *Deng et al.*, 2010] and are thought to be generated by the perpendicular electron temperature anisotropy resulting from betatron acceleration that occurs as the magnetic field strength increases inside the FPR [see e.g. *Wu et al.*, 2013; *Fu et al.*, 2014; *Huang et al.*, 2015b; *Wu et al.*, 2015]. *Deng et al.* [2010] investigated the properties (namely propagation angle, degree of polarization and ellipticity) of whistler waves inside the magnetotail FPR, and by analyzing Poynting flux, *Khotyaintsev et al.* [2011] have shown that these waves are generated near the geomagnetic equator.

Recently, multi spacecraft missions such as Cluster and THEMIS have allowed study of the detailed dynamics of BBFs. The fine structure of DFs has been investigated using the tetrahedron configuration of Cluster constellation by *Fu et al.* [2012b] [see also *Schmid et al.*, 2015]. They concluded that on a global scale DFs are tangential discontinuities, although *Balikhin et al.* [2014] observed oscillations within a few DF magnetic ramps which would indicate field-aligned currents causing the plasma to flow across DFs. The radial separation along the magnetotail of the THEMIS fleet also helped to investigate the spatial evolution of BBFs [*Runov et al.*, 2009; *Sergeev et al.*, 2009]. In particular, *Runov*

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et al. [2009] showed [see also *Sitnov et al.*, 2009, 2013; *Fu et al.*, 2013; *Angelopoulos et al.*, 2013] that BBFs are consistent with magnetotail reconnection outflows and thus DFs originate from pulses of reconnection. Front-like structures may also appear due to the kinetic ballooning/interchange instability (BICI), forming finger-like structures [*Pritchett and Coroniti*, 2010, 2013; *Pritchett et al.*, 2014]. However, reconnection and interchange are not necessarily mutually exclusive, as the edge of a reconnection jet was shown to be interchange unstable [e.g. *Nakamura et al.*, 2002; *Runov et al.*, 2012], and localized reconnection could be triggered in the wake of interchange heads [*Pritchett and Coroniti*, 2011, 2013]. Nevertheless, the THEMIS inter-spacecraft separation distances are never smaller than the typical ion inertial length ($\sim$ 500 km) in the tail and do not allow study of the subprotonic dynamics of DFs.

In May 2015, the MMS [*Burch et al.*, 2016] constellation was in the near-Earth tail in a string-of-pearl configuration, with a very small separation distance ($\sim$ 160 km) between each spacecraft that allows us to study BBF propagation below ion scales. In this paper we take advantage of this unique configuration to investigate the spatial evolution of two DFs on 15 may 2015 and their associated whistler emissions. In Section 2 we first determine the propagation properties of the two DFs and then we show the low-frequency wave dynamics associated with this event. The results are discussed and summarized in Section 3.

2. Data analysis

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Fig.1 gives an overview of the events observed on May 15, 2015 from 03:07:00 to 03:13:00 UT by the four MMS spacecraft located at [-11.7, 1.11, 1.14] R_E in GSE coordinates. Because B_x is smaller than 10 nT, MMS was close to the magnetic equator. Only magnetic and electric field waveforms (all three components of each are obtained from DFG [*Russell et al.*, 2016], and ADP [*Ergun et al.*, 2016] and SDP [*Lindqvist et al.*, 2016] instruments, respectively) as well as probe-to-spacecraft potential are presented in this figure, as FPI [Fast Plasma Investigation, see *Pollock et al.*, 2016] instrument was turned off at this time during the commissioning phase. Two dipolarization events can be distinguished at about 03:08:10 and 03:11:55 UT, characterized by a steep magnetic ramp of the B_z component from -1 and 5 nT to 9 and 10 nT in about 8 and 5 s, respectively. The inclination of the magnetic field increases simultaneously of about 40 and 25 degrees, respectively, and the maximum inclination angle is $\theta_{max} \geq 45°$ for both events. However, the first DF is accompanied by a high-speed flow ($v \geq 150$ km/s) whereas the second DF is not. For these two events, the behavior of the B_x component is similar (increase before and at the B_z ramp), however it is opposite for B_y (B_y decreases at the second DF).

The variations of plasma density n, inferred from probe-to-spacecraft potential, are also opposite for the two DFs: the density increases slightly at the first DF (at 03:07:50 UT) but then decreases (fluctuations of $|B|$ and n are out of phase, as in fast modes), whereas at the second DF the density decreases at 03:11:50 UT and then increases behind the DF (fluctuations of $|B|$ and n are in phase, as in slow modes). These two types of

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density signatures have been observed in statistical studies [*Schmid et al.*, 2011; *Schmid et al.*, 2015] and the first DF seems to fall in categories A/D while the second DF falls in category B/C in the classification established by *Schmid et al.* [2015]. In addition, just before the first DF a very sharp potential (i.e., density) drop is observed, along with a decrease/increase of B_z/B_x resulting in a slight increase of $|B|$ ahead of the magnetic ramp (see Fig.1). These features are discussed in the following section.

We perform a minimum variance analysis [MVA, see e.g. *Sonnerup and Cahill*, 1967] at the two DFs for all spacecraft to determine the propagation properties of the normal to the front. The minimum variance directions (MVDs) calculated for the extent of the magnetic ramp of the first DF are [0.55, -0.83, 0.07], [0.48, -0.87, 0.05], [0.46, -0.88, 0.04], [0.43, -0.9, 0.03] for MMS1, MMS2, MMS3 and MMS4, respectively. The MVDs for the first DF are well defined on all spacecraft with a ratio of the intermediate to minimum eigenvalues in the range [8-10] and a ratio of maximum to intermediate eigenvalues in the range [3-4]. The normal of the first DF is thus mostly directed along Y. For the second DF the MVDs are less well defined, thus in this paper we choose to study in detail the propagation properties of the first DF.

The normal to the first discontinuity (i.e. the direction of propagation of the first DF) derived from the MVA performed on each spacecraft is sketched in Fig.2. The normal of the first DF rotates significantly (the Y component decreases whereas the X and Z components increase) between each spacecraft in the XY and XZ planes, i.e. on a scale of $\sim$ 500 km, during its earthward propagation. In the absence of bulk plasma

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measurements, we determine the velocity of the convected plasma of the FPR (where the plasma is convected and the Hall term is small [*Li et al.*, 2011; *Fu et al.*, 2012a]) in the MVA frame as $(E \times B)/B^2 \approx 150$ km/s and directed along the minimum variance direction for the first DF (see Fig.1e). Assuming the duration of the front (i.e. the magnetic ramp) as $\Delta t \approx 8$ s (see the B_z component in 1), we estimate the spatial scale (thickness) of the DF as $\Delta d \approx 1200$ km (i.e. $\sim 2.5\rho_i$, ρ_i being the ion gyroradius). The standard timing analysis [see Eq.12.9 from *Paschmann and Daly*, 1998] fails in our case (string-of-pearls configuration) because it requires the 4 spacecraft to be non-coplanar. However, the normals calculated for MMS4 and MMS3 are close to the plane determined by the alignment of the 4 spacecraft (see Fig.1), which is confirmed by the sequential observation of the DF by C4 and C3. The B_z profiles observed by MMS4 and MMS3 are also very similar, meaning we can do the timing unambiguously. Thus, by simply time-shifting the B_z data from MMS4 and MMS3, we can estimate roughly the velocity of DF. We determine $\delta t \approx 1$ s between the 2 spacecraft and thus the velocity of the DF as $v_{DF} = \delta d/\delta t \approx 160$ km/s along the spacecraft separation, with an uncertainty of ~ 50 km/s. Taking into account the uncertainties on both velocity estimates ($E \times B/B^2$ and timing) the convective velocity and the discontinuity velocity can be considered as equal therefore the first DF can be characterized as a tangential discontinuity. These results and their probable causes are discussed in the following section.

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150 We also perform an analysis of E- and B-fields fluctuations in the frequency range [1-64] 151 Hz, i.e. between the ion and electron gyrofrequencies, obtained from ADP, SDP and SCM 152 [*Le Contel et al.*, 2016] instruments. The results of this analysis for MMS2 are summarized

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in Fig.3. We observe very strong electrostatic fluctuations close to the lower-hybrid (LH) frequency exactly at the time of the first DF (∼03:08:10 UT). These are thus probably LH waves, as inherently observed at DFs [*Deng et al.*, 2010; *Khotyaintsev et al.*, 2011; *Huang et al.*, 2012]. Behind the first front we also observe strong electromagnetic fluctuations with a frequency just above $0.1f_{ce}$ (white line in Fig.3, f_{ce} being the electron gyrofrequency) and a highly (degree of polarization > 0.9) right-handed (ellipticity ≈ 1) polarized, as well as a low propagation angle to the background magnetic field ($\theta \leq 20°$). Thus, these fluctuations are likely whistler waves, as often observed behind DFs [*Khotyaintsev et al.*, 2011; *Fu et al.*, 2014; *Viberg et al.*, 2014; *Li et al.*, 2015]. Weaker LH and whistler waves are also observed at and behind the second DF (∼03:11:55 UT), which is also weaker in ΔB_z. However, the whistlers behind the second DF propagate obliquely ($\theta \approx 40 - 50°$) to the background magnetic field. In addition, although most of whistlers propagate towards the magnetic equator (anti-parallel Poynting flux), we observe whistlers with a reversed Poynting flux (parallel to magnetic field) at about 03:08:45 UT, with less intensity as seen on magnetic and electric spectra. These results are discussed in the following section as well.

The same analysis was conducted on other spacecraft (not shown) resulting in similar wave properties (degree of polarization, wave angle, ellipticity and Poynting flux) for this time interval. However, there is a clear evolution of magnetic spectra observed at the different spacecraft, as shown in Fig.4. The latter displays enhanced magnetic fluctuations along the BBFs trajectory so that MMS1 (which is closer to the Earth, see Fig.2) observes strong whistlers at 03:08:55 UT whereas MMS4 does not. Whistlers behind the second

DF are also stronger on MMS1 than on MMS4 (see Fig.4). This wave growth enhances the electromagnetic power by about 2 orders of magnitude (from about 2.10^{-10} on MMS4 to 1.10^{-8} W/m^2 on MMS1) behind the first DF and about 1 order of magnitude (from $\sim 1.10^{-10}$ to 1.10^{-9} W/m^2) behind the second DF, as seen on Fig.4. Fig.4 also shows that quasi-parallel whistlers at 03:08:55 UT are (about one order of magnitude) less intense than anti-parallel ones.

3. Summary and discussion

In May 2015, the newly launched MMS fleet was orbiting Earth in a string-of-pearls configuration. For the first time such configuration with very close spacecraft separation distance (~ 160 km) flew through the near-Earth magnetotail ($\sim 10-12R_E$). Making use of this unique opportunity, in this study we investigate the small-scale (i.e., below the ion gyroradius) dynamics of DFs propagation in the tail and their associated low-frequency emissions.

Our results can be summarized as follows: 1) two DF structures are identified, both generated at the magnetic equator and propagating earthward, but they are probably of different nature: based on the density variations therein, they fall into different categories of DFs [*Schmid et al.*, 2015]. 2) The first DF is probably a tangential discontinuity and is very dynamic: its normal rotates towards Earth on spatial scales less than the ion gyroradius (~ 500 km). 3) Both DFs show strong associated low-frequency waves (LH at DF and whistlers behind it) but with different properties: while intense quasi-parallel whistlers are observed behind the first DF, weaker oblique whistlers are observed behind the second one. 4) The dynamics of whistler waves associated with the first DF are also subprotonic: in less than 5 seconds $|B|$ increases (i.e. the flux tube is compressed) as the DF propagates earthward (from MMS4 to MMS1) and the whistler electromagnetic power is enhanced by 1 to 2 orders of magnitude. Some wave packets are observed to have a reversed (anti-parallel) Poynting flux within the FPR. However, these results raise some questions that we discuss in the following paragraph.

As deduced from the MVA, the two DF events in this study seem to be generated in the midtail (they propagate earthward) at the magnetic equator, in agreement with models [*Runov et al.*, 2011; *Sitnov et al.*, 2013; *Nakamura et al.*, 2002; *Pritchett et al.*, 2014] and previous observations [e.g. *Le Contel et al.*, 2009]. The normal of the first DF in the XZ plane is first directed northward (XZ plane) and dawnward (XY plane) but then rotates earthward (components in Y, Z directions decrease, X component increases) during its propagation, on a spatial scale ($\sim$ 500 km) less than the ion gyroradius. This subprotonic-scale rotation of the DF might for instance modify the dynamics of accelerated high-energy particles in the vicinity of the DF (such as for instance reflected ions ahead of the DF as described in [*Zhou et al.*, 2010]). Detailed analysis of such particle measurements using MMS data and dedicated numerical simulations are thus necessary to determine the effects on particle dynamics at these scales. The MVDs calculated for the first front are clearly defined, in contrast with the MVDs calculated for the second DF; presumably because the second DF is located in the "turbulent trail" of the first DF, as the magnetic field from ~03:09:50 to 03:12:00 UT appears to be highly fluctuating. Nevertheless, particle measurements are needed to study turbulence in the vicinity of DF [*Huang et al.*, 2012] and in BBFs [*Vrs et al.*, 2004; *Vörös et al.*, 2006], and this issue is thus beyond the scope of this study.

The estimation of the bulk plasma (as deduced from $(E \times B)/B^2$) and discontinuity (roughly estimated from timing analysis) velocities give rather similar values ($\sim$ 150 km/s) and the bulk velocity is directed along the front normal, thus this DF seems to be a tangential discontinuity [*Schmid et al.*, 2011; *Fu et al.*, 2012b]. Additionally, fluctuations in the magnetic ramp are weak, thus field-aligned currents at the DF must not be strong and the plasma flow crossing the instability may not be significant [*Balikhin et al.*, 2014; *Huang et al.*, 2015b]. In addition, a significant drop in density (inferred from probe-to-spacecraft potential) over about 20s is observed about 30 s ahead of the first DF (at $\sim$03:07:35). This steep density hole is accompanied by a singular magnetic signature (slight increase in B_x and decrease in B_z components, see Fig.1), whereas no particular electric fluctuations are observed at this time (e.g. on MMS2, see Fig.3). This could be the signature of the earthward propagation of a DF as a flux rope, as depicted in the multiple reconnection X-lines (MRX) model [see e.g. *Lee*, 1995; *Slavin et al.*, 2003; *Huang et al.*, 2015; *Lu et al.*, 2015]. In particular, *Lu et al.* [2015] have performed a 3D hybrid simulation of DFs as earthward propagating flux ropes, and has shown that the multiple X line reconnection process gives birth to flux ropes that propagate earthward with a B_z and plasma density dip signature (as observed on Fig.1) ahead of them [see Fig.1b to e in *Lu et al.*, 2015], especially if a previously formed flux rope is located closer to the Earth [see Fig.1c in *Lu et al.*, 2015]. However, the exact nature of this phenomenon is still to be determined and we leave this for future studies.

Intense low-frequency waves are also observed at (LH) and behind (whistlers) DFs. The calculation of Poynting flux (see Fig.3) seems to indicate that they propagate towards the magnetic equator. However, the presence of the two sudden reversals in their direction of propagation and the fact that B_x oscillates around zero when they are observed, suggest that the spacecraft are located in the whistler generation region close to the magnetic equator [*Le Contel et al.*, 2009; *Runov et al.*, 2011]. This propagation direction is consistent with the position of the spacecraft at that time ($Z_{GSE} \approx 1.14R_E$). Whistlers become more intense closer to the Earth as $|B|$ increases from MMS4 to MMS1 when they are observed, indicating that the perpendicular anisotropy may vary at the time scale of the ion gyroperiod (~ 2 s). From 4 a very rough estimation of the growth rate gives $\gamma \approx 0.001\Omega_e$, $\Omega_e \approx 200$ Hz being the electron gyro-pulsation (see right panels on Fig.4). This result is consistent with growth rates calculated from models with similar plasma parameters [see e.g. first plasma model from *Le Contel et al.*, 2009]. However, to accurately determine the temperature anisotropy, data particle are needed and we leave this for future study.

Whereas the whistlers at the first DF are quasi-parallel, those observed behind the second front are oblique to the magnetic field. As stated above, the estimation of density variations indicate that, according to *Schmid et al.* [2015] classification, the two DFs in this study may be of different nature. Thus it might be possible that the properties of whistlers associated with DFs are dependent on the nature of these DFs, as different pitch angle distributions of suprathermal electrons have been observed behind different types of DFs [*Fu et al.*, 2011; *Fu et al.*, 2012c]. However, a statistical study of low-frequency emissions associated to DFs of different nature is necessary and is left for future investigation.

To conclude, the subprotonic dynamics of DFs (rotation of the normal on a scale ~ 500 km) and their associated low-frequency emissions (whistler waves intensification) in the magnetotail are shown for the first time due to the small separation distance (~ 160 km) of MMS string-of-pearls configuration in May 2015. Unfortunately, the FPI instruments were not turned on at that time so only electromagnetic fields data are presented. Observations in phase 1X (starting in March 2016) will also have FPI instruments turned on very sparsely and moreover the apogee in the nightside will be located far from the magnetic equator ($Z \approx 5R_E$). Thus the events shown in this paper represent a unique opportunity to study the kinetic-scale dynamics of DF propagation and associated whistler emissions.

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Fig1-eps-converted-to.pdf

Figure 1. Summary of DFG and EDP measurements onboard the four MMS spacecraft, on the 15th of May 2015 between 03:06:00 and 03:14:00 UT. From top to bottom panels are: the modulus of magnetic field B, the x, y and z components, the convected plasma velocity ($\vec{E} \times \vec{B}$) along the DF normal and the probe-to-spacecraft potential.

Fig2.pdf

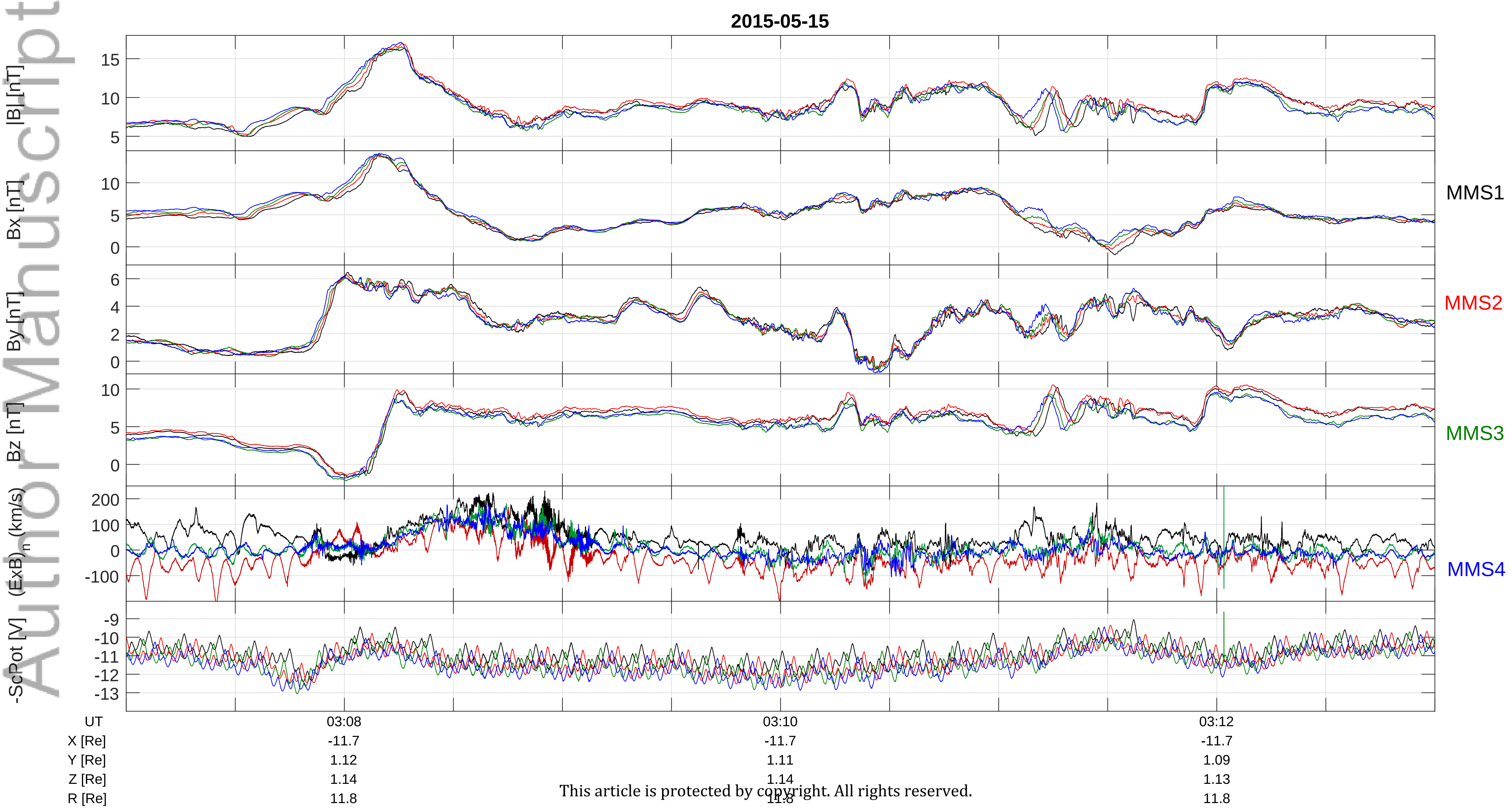
Figure 2. Sketch (not on scale) of the MVDs of the first DF obtained onboard all four MMS spacecraft, in the equatorial XY (left panel) and meridional XZ (right panel) planes in GSM coordinates. The gray arrows depict the DF propagation inferred from the MVDs for the sake of clarity.

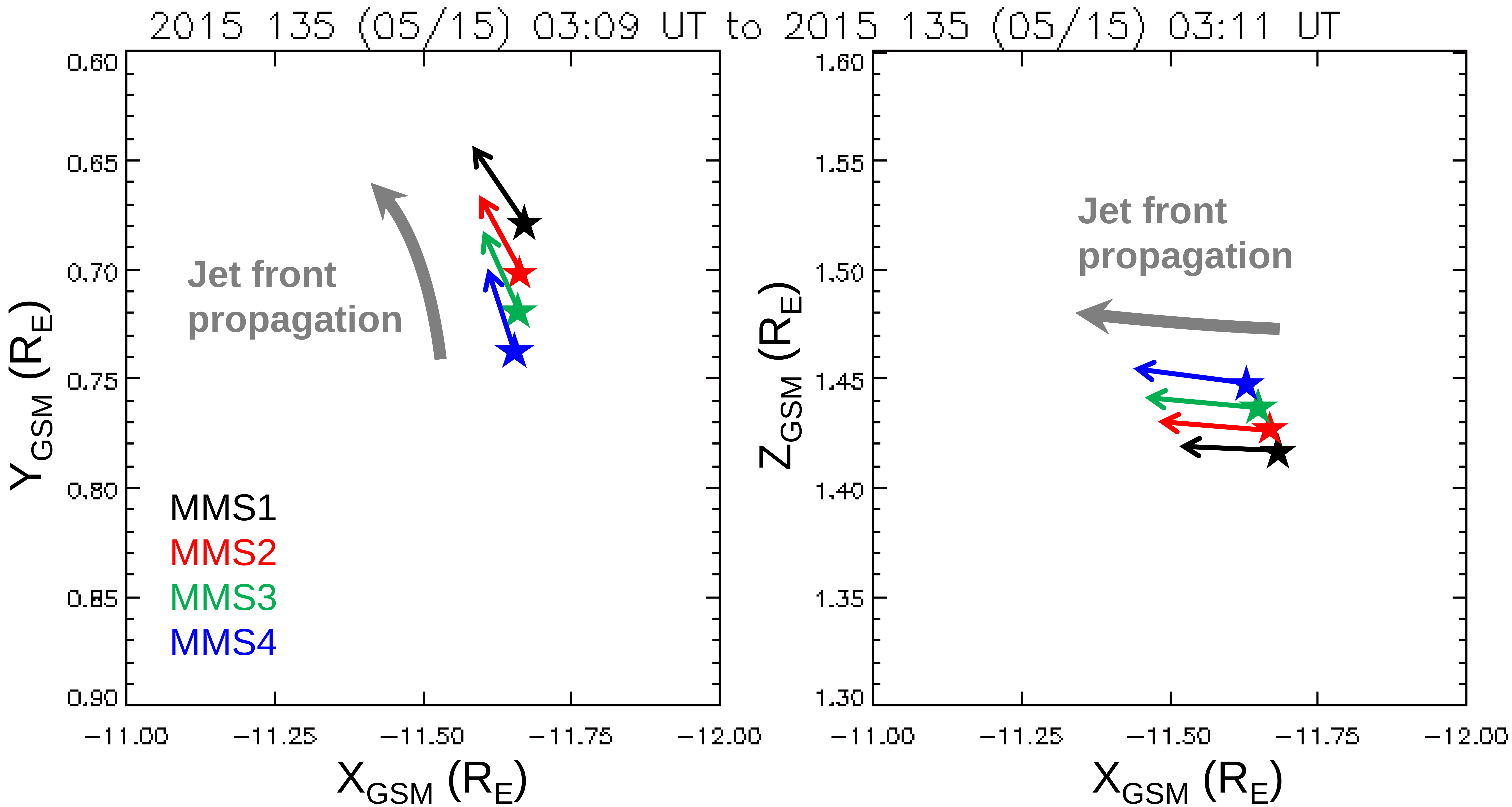
Fig3-eps-converted-to.pdf

Figure 3. Example of detailed wave analysis performed on MMS2 in the frequency range [1-64] Hz: the magnetic (panel a) and electric (panel b) field waveforms from DFG and EDP instruments in DMPA and DSL coordinates, respectively, are color coded. The time-frequency spectrograms computed from these waveforms are shown in panels c and d, respectively. The degree of polarization, propagation angle θ_k (between $\vec{k}$ and $\vec{B_0}$), ellipticity and Poynting flux angle θ_S (between $\vec{S}$ and $\vec{B_0}$) are also displayed in panels e, f, g and h, respectively.

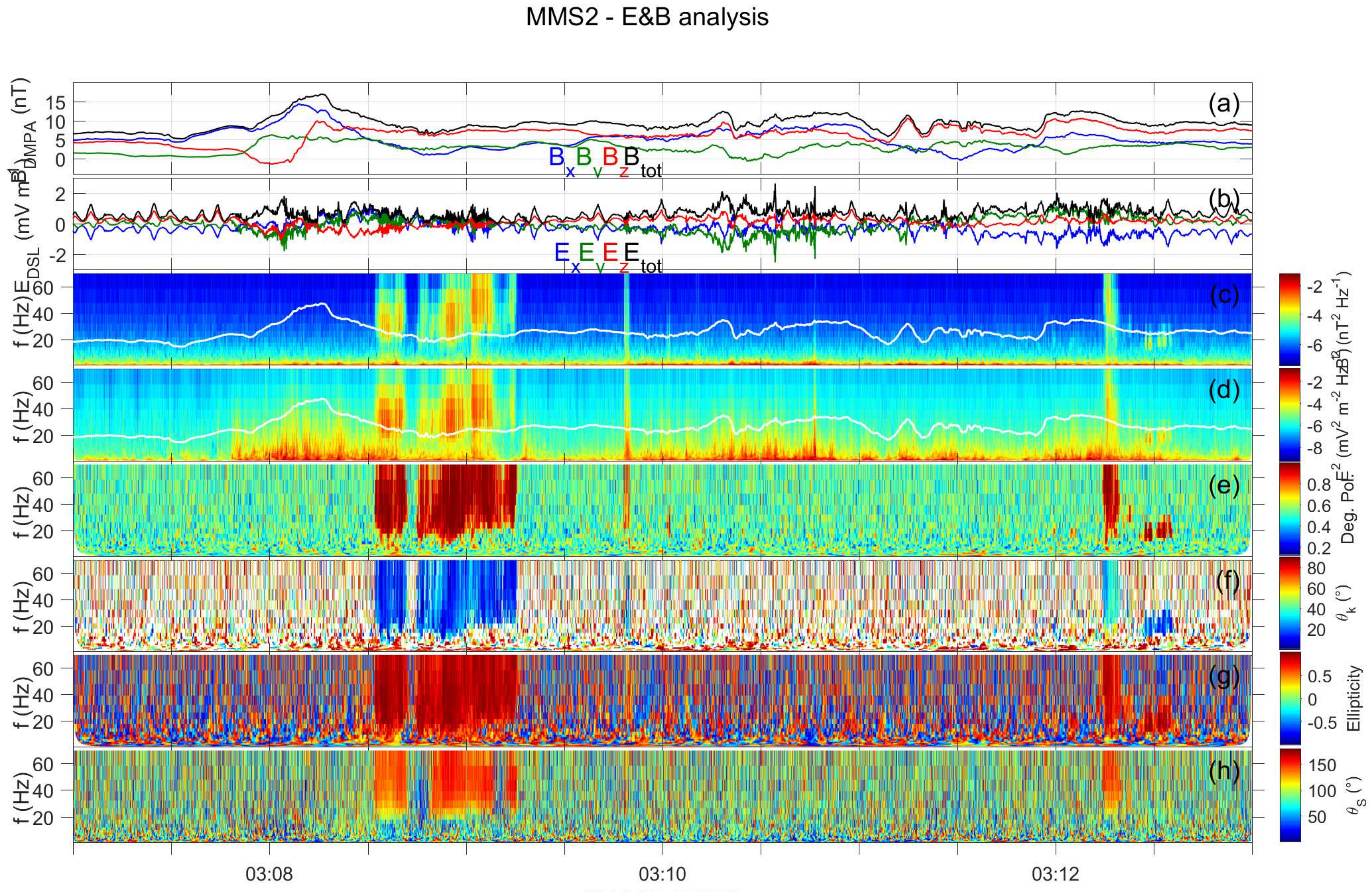
Fig4.pdf

Figure 4. The total electromagnetic power (irradiance), computed from the Poynting flux, is shown (left panels) for all four spacecraft (from top to bottom MMS 1, 2, 3, 4) along the DF propagation (gray arrow). A zoom-in on 03:08:15 to 03:09:30 UT for each spacecraft (right panels) shows the evolution of time-frequency spectrograms of whistler waves.

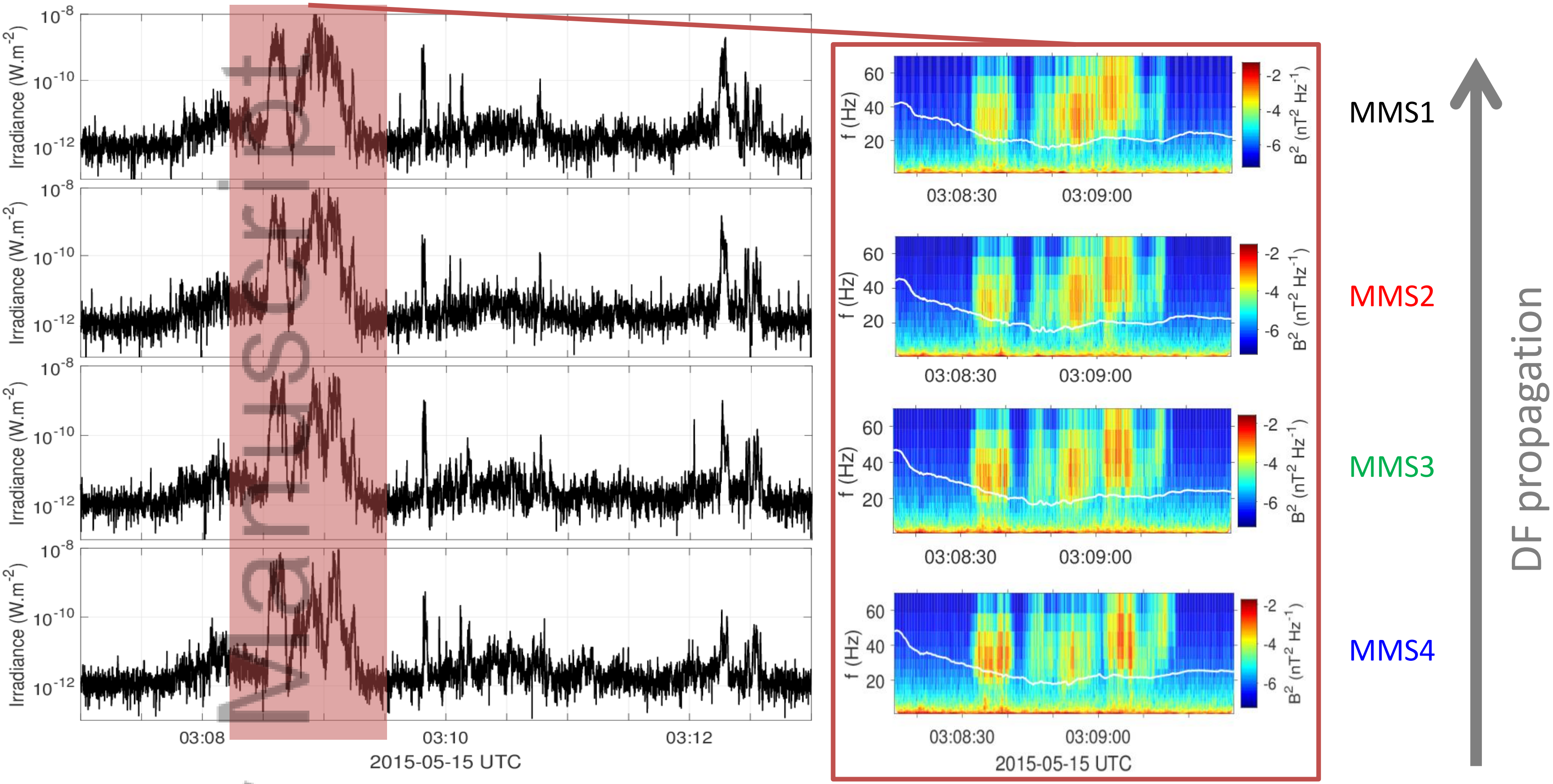

2015-05-15
|B| [nT]
Bx [nT]
By [nT]
Bz [nT]
(ExB)n (km/s)
-ScPot [V]
MMS1
MMS2
MMS3
MMS4
UT
X [Re]
Y [Re]
Z [Re]
R [Re]
03:08
-11.7
1.12
1.14
11.8
03:10
-11.7
1.11
1.14
11.8
03:12
-11.7
1.09
1.13
11.8



2015 135 (05/15) 03:09 UT to 2015 135 (05/15) 03:11 UT
0.60
0.65
0.70
0.75
0.80
0.85
0.90
Y_GSM (R_E)
Jet front propagation
MMS1
MMS2
MMS3
MMS4
−11.00
−11.25
−11.50
−11.75
−12.00
X_GSM (R_E)
1.60
1.55
1.50
1.45
1.40
1.35
1.30
Z_GSM (R_E)
Jet front propagation
−11.00
−11.25
−11.50
−11.75
−12.00
X_GSM (R_E)



MMS2 - E&B analysis
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
B_DMPA (nT)
Bx By Bz Btot
E_DSL (mV m-1)
Ex Ey Ez Etot
f (Hz)
B² (nT² Hz⁻¹)
E² (mV² m⁻² Hz⁻¹)
Deg. PoF
θk (°)
Ellipticity
θS (°)
03:08
03:10
03:12
2015-05-15 UTC



Irradiance (W.m^{-2})
10^{-8}
10^{-10}
10^{-12}
03:08
03:10
03:12
2015-05-15 UTC
f (Hz)
60
40
20
03:08:30
03:09:00
B^2 (nT^2 Hz^{-1})
-2
-4
-6
MMS1
MMS2
MMS3
MMS4
DF propagation