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AC magnetic field measurements onboard Cross-Scale: scientific objectives and instrument design

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Abstract

The ACB search-coil magnetometer for Cross-Scale will measure three components of the AC magnetic field up to 4 kHz, and one component up to 100 kHz. Turbulent and coherent magnetic field fluctuations in the frequency range of ACB play an important role in the acceleration, scattering, and thermalisation of particles; ACB observations will, together with the other instruments of the wave consortium, allow to address the key science objectives associated with plasma waves. We focus on some of the important issues, based on the experience drawn from Cluster.

Key words: space plasmas, AC magnetic field, measurements, turbulence, shocks, reconnections

1. Introduction

AC magnetic field fluctuations are among the key quantities to be measured in order to achieve the scientific goals of the Cross-Scale mission. The three major targets of the project (shocks, reconnection and turbulence) being fundamentally dynamic in their nature, a proper identification of the different types of waves is indeed crucial. The ACB search-coil magnetometer will measure three components of the fluctuating magnetic field in the ELF/VLF frequency range (1 Hz - 4 kHz), and one component in the

9 VLF/LF frequency range (1 kHz - 100 kHz). Here, we detail some of the
10 issues that will be addressed by ACB, using the experience gathered from
11 Cluster.

12 **2. Relevance of ACB for turbulence studies**

13 Space plasmas are collisionless and are subject to a variety of instabilities
14 that generate many different plasma wave modes. These waves are expected
15 to play a major role in the dissipation of turbulent energy. In contrast to
16 neutral fluid turbulence, where the energy cascade between scales follows
17 universal power scaling laws over several decades, in plasma turbulence, im-
18 portant effects like plasma heating, particle scattering and acceleration are
19 linked to fluctuations on the gyroscopes of ions and electrons. On these scales,
20 there are many wave modes, both electromagnetic and electrostatic, that can
21 participate in the transfer of turbulent energy into particle heating through
22 wave-particles interactions. Obviously, the dissipation process in collisionless
23 plasmas is much more complex than in neutral fluids and scale invariance is
24 expected to break down at dissipation scales.

25 With Cross-Scale it will become possible to answer several of the open
26 key questions concerning the nature of the turbulent cascade, particularly
27 near the ion and electron kinetic scales. These issues are discussed more in
28 detail in Sahraoui and Dudok de Wit (2009); we list here some of them.

29 *2.1. Dissipation processes in plasma turbulence*

30 By applying the k -filtering technique (Pinçon and Lefeuvre, 1991) to ACB
31 measurements, it will become possible to determine the 3D full spectra for
32 both the field energy and magnetic helicity in frequency and wave vector
33 domain. For the very first time, the obtained spectra will include both ion
34 and electron scales, thereby offering the opportunity to directly and unam-
35 biguously identify the expected change in the turbulence cascade. From the
36 3D field energy spectra in frequency and wave vector domain we will have
37 the possibility: first, to identify the relation dispersion for wave modes at
38 electron and ion scales; second, to compare the field energy associated with
39 these modes with the total energy cascading at each scale. Such informa-
40 tion will provide a real insight into the nature of the dissipation processes
41 occurring in plasma turbulence. Moreover, the performances of the particle
42 instruments onboard Cross-Scale will offer the unique opportunity to study
43 the partition of energy between particles and fields. From the distribution

44 function of ions and electrons with 1 s and 0.1 s resolution, respectively, the
45 kinetic energy distribution of both ions and electrons will be estimated and
46 compared with the field energy at the dissipation scales.

47 Although the performances of ACB fulfill the requirements of the Pay-
48 load Definition Document (Wieters and Cross-Scale Science Study Team,
49 2008), actual needs in term of sensitivity still have to be examined carefully.
50 Indeed, recent results from Cluster suggest that a sensitivity better than
51 $10^{-5}nT/(Hz)^{1/2}$ at 100 Hz is required to resolve unambiguously the physics
52 of the solar wind dissipation range at 1 AU.

53 *2.2. Anisotropy and coherent structures*

54 In space plasmas the presence of a prevalent magnetic field direction
55 breaks down the isotropy of plasma turbulence. The way this anisotropy
56 develops from the injection scale to the dissipation scale and the details of
57 the energy transfer processes are still poorly understood. ACB measurements
58 onboard Cross-Scale will let us track the development of anisotropy between
59 scales for the first time. To complete this study, particle measurements will
60 be used to evidence the mass transport. In the same way, ACB will help
61 identify coherent structures, measure their growth and development as they
62 travel past the fleet of satellites, and to quantify their effect on the turbulent
63 cascade.

64 Another issue is the identification of vortex-like structures by making
65 use of multi-point measurements that have allowed to identify turbulence
66 elementary entities in the cusp region (see fig.1).

67 The shorter spacecraft separation of Cross-Scale (as compared to Clus-
68 ter) will greatly help in the determination of wave sources from inter-satellite
69 correlations. (Agapitov et al., 2009), for example, recently managed to use
70 Cluster observations to characterise the sources and properties of turbulent
71 plasma inhomogeneities in the radiation belts. Such studies will be consid-
72 erably easier with Cross-Scale.

73 *2.3. Extending the frequency range of ACB*

74 ACB, in contrast to most existing search-coil magnetometers, will also
75 probe a higher frequency range that extends from 1 to 100 kHz. To motiva-
76 tion for adding this extension, which was optional in the Payload Definition
77 Document (Wieters and Cross-Scale Science Study Team, 2008) is threefold.

78 Electron acceleration by shocks and high frequency waves is an important
79 indicator of acceleration processes. Recent studies by Lobzin et al. (2005) of

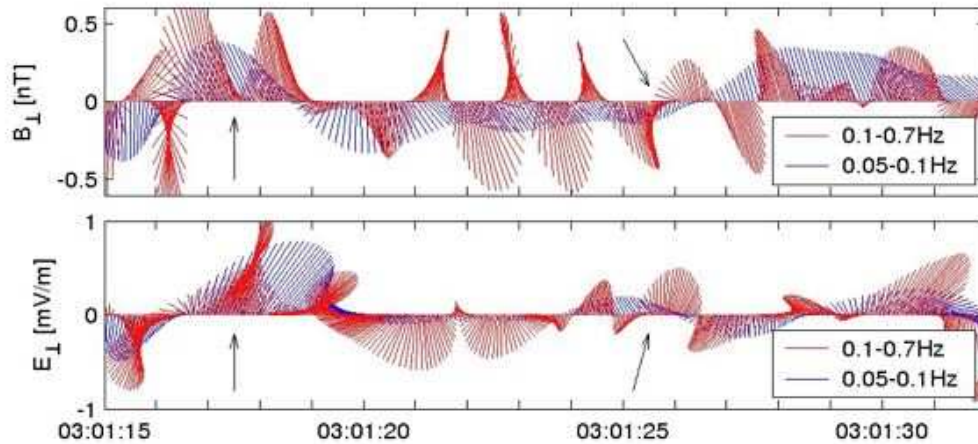


Figure 1: New point of view on data analysis: look for coherent structures by examining time-series from several spacecraft simultaneously. The rotation of electric and magnetic field vectors is spatially coherent in agreement with the vortex convection past the spacecraft. After Sundkvist et al. (2005).

80 so-called downshifted oscillations have shown that different types of waves
 81 are associated with the features of the electron distribution functions; such
 82 waves are a consequence of the interaction of the shock front with the incident
 83 electrons; their frequency is typically several kHz. First studies were carried
 84 out using ISEE and later with Cluster. Their electromagnetic nature remains
 85 uncertain due to the lack of adequate magnetic field measurements in that
 86 frequency range.

87 Intensive electron fluxes were observed by the Cluster satellites in the
 88 vicinity of the reconnection electron diffusion region around the magne-
 89 topause (Khotyaintsev et al., 2004). These structures were found to be quite
 90 narrow, preventing particle instruments from performing correct measure-
 91 ments of the electron distribution functions. The only available diagnostics
 92 in this case are high frequency wave measurements. Electric field spectra in-
 93 deed revealed the presence of intense oscillations around the presumed local
 94 electron plasma frequency. Here again, ACB will help determine whether
 95 these waves are electrostatic or electromagnetic.

96 Finally, an important aspect of turbulence studies is the generation of
 97 electrostatic and electromagnetic high frequency waves in the vicinity of the
 98 acceleration regions such as shock or the magnetopause. Two examples are

99 type II solar radio bursts, and similar wave activities in the vicinity of the
100 Earth bow shock. The plasma in these areas is strongly inhomogeneous and
101 the processes that generate and convert waves can be linear and nonlinear.
102 It was shown by Bale et al. (1998) and by Kellogg et al. (1999) that the
103 observed waves often belong to the electromagnetic branch rather than to
104 the electrostatic one. Such studies require simultaneous measurements of
105 the magnetic and electric fields up to frequencies of several tens of kHz.

106 There are several other examples, such as the generation of harmonics of
107 the electron gyro frequency (Sundkvist et al., 2006), where the simultane-
108 ous measurement of magnetic and electric fluctuations provides considerable
109 added insight. All these problems can be addressed if the frequency range of
110 the nominal ACB instrument is extended to 100 kHz, see Sec. 5.

111 **3. Relevance of ACB for shocks studies**

112 Cross-Scale will observe the high variability and the reformation the
113 Earth's bow shock with considerably better resolution than Cluster. To do
114 so, DC magnetic field measurements will be required but also AC measure-
115 ments with, for ion scales, a separation < 1000 km and cadence of 0.1 s for 4
116 spacecraft, and for electron scales a separation of < 100 km with a cadence
117 of 0.01 s for 4 spacecraft.

118 Cluster has provided only few observations of the non-stationary dynam-
119 ics of the bow shock. Figure 2 shows the January 24, 2001 event, which
120 had intense wave activity and exhibited strong variations of the reflected
121 ion number density. Whistler waves generated in the ramp region are found
122 to propagate upstream. The relatively small separation (100 km) of Cross-
123 Scale will allow to perform cross-correlation studies that were not feasible
124 with Cluster.

125

126 An important issue in the study of the shock reformation is the determina-
127 tion of the energy fluxes (Poynting vectors) of the Whistler waves generated
128 near the shock front. This requires both AC electric and magnetic field mea-
129 surements. Cluster orbits are not appropriate for such studies as they're
130 often too tangential to the shock front.

131 **4. Relevance of ACB for reconnection studies**

132 Cross-Scale will for the first time cover the electron, ion and fluid scales
133 simultaneously and thereby help unravel the way or ways in which recon-

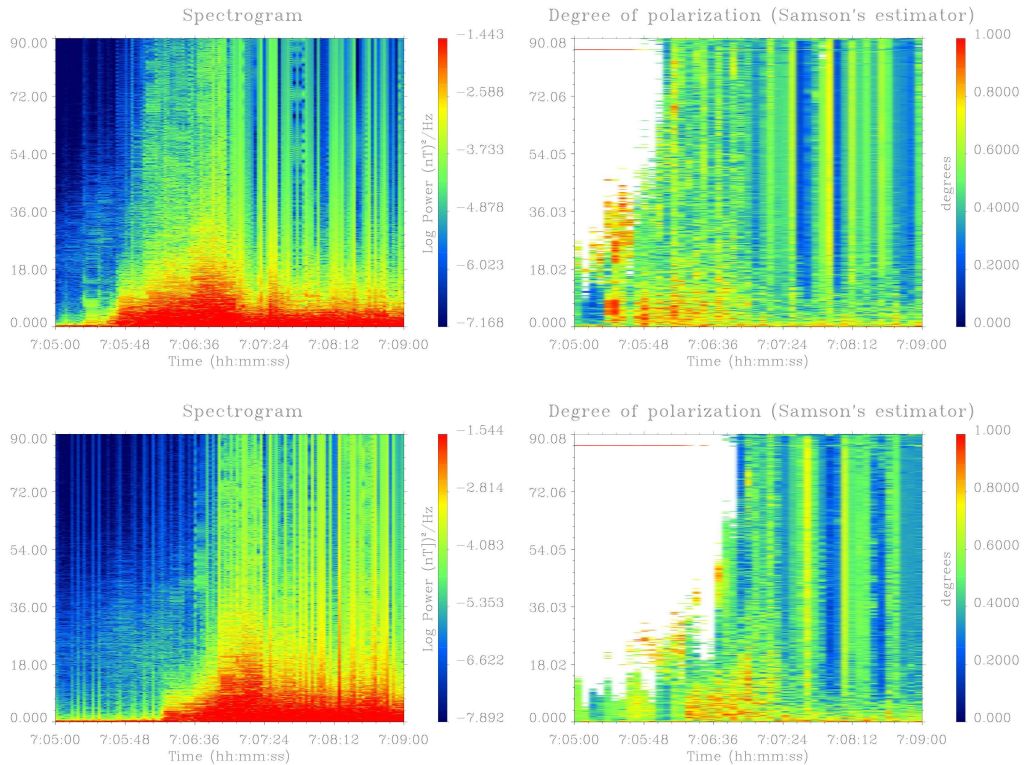


Figure 2: Time-frequency representation of the wave intensity (left) and degree of polarisation (right) of the AC magnetic field fluctuations measured by the STAFF search-coil onboard two Cluster spacecraft during the Earth's bow shock crossing on January 24 2001.

134 nection arises, operates, and controls large scale dynamics. One of the key
 135 questions here is the onset of reconnection. To distinguish the ambient fields
 136 and the thin current layer, simultaneous multipoint measurements of the AC
 137 magnetic and electric fields are requires over a wide range of frequencies and
 138 with temporal resolutions up to 1 ms for the spectral matrix.

139 What matters here is the proper identification of the various signatures of
 140 reconnection. Enhanced high frequency fluctuations are expected to occur at
 141 the reconnection onset, when instability-driven turbulence enhances anomalous
 142 resistivity, or when waves interact with electrons, causing instabilities to
 143 grow. These electromagnetic disturbances are probably spatially structured
 144 down to the smallest (i.e. electron) scales. AC electric and magnetic fields

145 up to kHz with cadence of 1 ms are required in that case.

146 Multipoint measurements of AC magnetic fields also allow weak inductive
147 electric fields to be detected. Such fields play an important role in creating
148 energetic tails in particle distributions and require measurements with a ca-
149 dence of at least 0.02s to resolve convected Hall scales (scales in-between
150 electron and ion scales).

151 It should be stressed that these measurements in the 10-100 Hz range
152 require high sensitivity. We are presently investigating whether it is worth
153 shifting the response of the sensors to slightly lower frequencies for that
154 purpose.

155 **5. Instrument description**

156 The ACB instrument consists of a triaxial search-coil that has a solid
157 technical heritage in many past missions (Cassini, Cluster, Demeter, Themis,
158 and more). Each sensor consists of a magnetic core with a winding whose
159 voltage is proportional to the time-derivative of the magnetic field (Séran and
160 Ferreau, 2005). Two major improvements have been brought with respect
161 to the STAFF search-coil instrument on Cluster (Cornilleau-Wehrin et al.,
162 1997).

163 First, while two sensors cover the ELF/VLF frequency range only from
164 1 Hz - 4 kHz, the third one is a dual-band sensor that covers both the
165 ELF/VLF and the VLF/LF (1 kHz - 100 kHz) ranges. On the latter, the
166 same core is used for two windings with a mutual reducer to decouple them
167 (Coillot et al., 2007). This design allows to extend the frequency range with a
168 mass increase of 12 g only, to be compared against the mass of a single-band
169 sensor, which is 59 g. The three sensors, each of which is 104 mm long, are
170 mounted orthogonally on a nonmagnetic support, see Fig. 3.

171 The second major improvement concerns the instrument and preamplifier
172 design. The 3-channel preamplifier will be built in 3D+ technology, and is
173 similar to the one that will be used on BepiColombo. The reduced size of
174 the preamplifier and its location inside the foot of the support allow for a
175 considerable mass saving with respect to the classical design with an external
176 preamplifier housed in a box and large connectors. Indeed, the total mass
177 of the instrument without harness reduces from over 728 g to 450 g. An
178 additional advantage is a higher thermal inertia, which matters for a mission
179 such as Cross-Scale, which will face long eclipses.

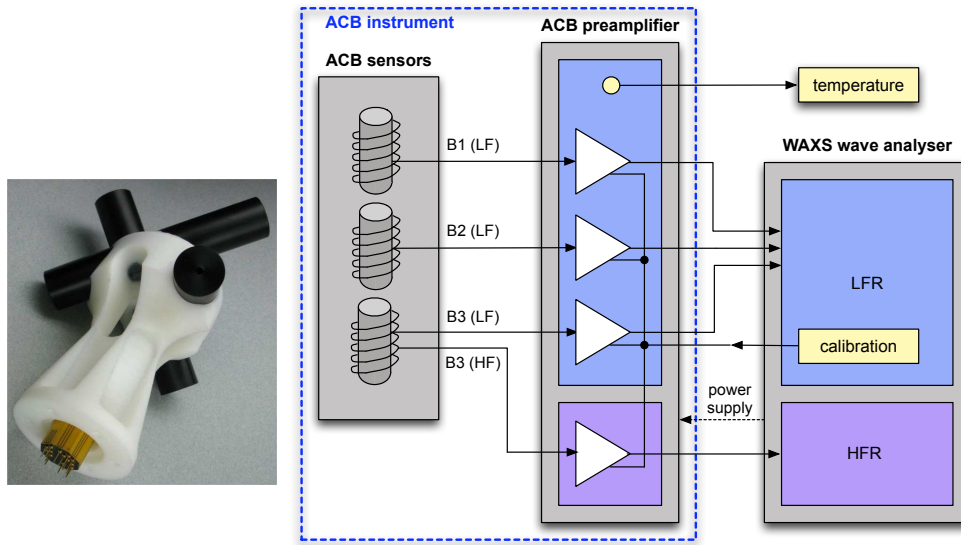


Figure 3: Sensor prototype to be used for ACB, showing the preamplifier in the foot (left figure). Block diagram of the instrument (right).

180 An additional improvement, which is now under study, is the replacement
 181 of the 3D+ technology preamplifier by one in ASIC technology. One of
 182 the main advantages is an additional mass saving, mostly because a smaller
 183 components require smaller shielding against radiations. Both the 3D+ and
 184 ASIC designs have already been tested with a total dose of 100 krad.

185 The sensitivity of the instrument is frequency-dependent, and drops from
 186 $2 \text{ pT/Hz}^{1/2}$ at 10 Hz to $10 \text{ fT/Hz}^{1/2}$ at 2 kHz, where it is minimal. The
 187 minimal sensitivity of the VLF/LF sensor is $10 \text{ fT/Hz}^{1/2}$ at 10 kHz. Because
 188 of this high sensitivity, electromagnetic cleanliness is a crucial issue for ACB.
 189 The sensors will be located on a boom at a minimal distance of 2 m from
 190 the spacecraft in order to meet the science requirements. It is essential,
 191 however, that the spacecraft design also meets the stringent requirements for
 192 electromagnetic cleanliness.

193 The analogue signals from ACB will be processed by the WAXS wave
 194 analyser, which will deliver either spectra or continuous waveforms up to
 195 500 Hz depending on the sampling strategy. These measurements will be
 196 synchronised with those from the E2D electric field instrument in order to
 197 allow for the full spectral matrix to be computed. Identical instruments

198 will fly on all Cross-Scale spacecraft. To summarise, the total mass of the
199 instrument will be 450 g, for a total power consumption of 0.2 W.

200 **6. Conclusion**

201 The ACB search coil will, together with the other instruments of the fields
202 consortium, allow to address the science objectives of Cross-Scale. This in-
203 strument has a solid technological and scientific heritage and yet, it will
204 bring several significant improvements as compared to existing multipoint
205 measurements. From a technological viewpoint, the instrument is smaller
206 and considerably lighter, owing to a better design. It will also extend the
207 frequency range up to 100 kHz, thereby the allowing the electromagnetic
208 nature of high-frequency waves to be investigated. This feature will be par-
209 ticularly useful for comparing electron to ion scale structures.

210 Even though AC magnetic field observations in space plasmas is now a
211 mature field, further technological improvements are under way. One is the
212 increased sensitivity of the sensors in order to provide better access to the
213 weak fluctuations in the solar wind dissipative range (Kiyani et al., 2009;
214 Sahraoui et al., 2009). This, however, can only be achieved at the expense
215 of a better electromagnetic cleanliness.

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