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1 **Measurements of magnetic field fluctuations for Plasma Wave Investigation by the search coil**
2 **magnetometers (SCM) onboard Bepicolombo Mio (Mercury Magnetospheric Orbiter)**

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32
33 **Abstract**

34 This paper describes the design and performance of the search coil magnetometers (SCM),
35 which are part of the Plasma Wave Investigation (PWI) instrument onboard the BepiColombo/Mio
36 spacecraft (Mercury Magnetospheric Orbiter), which will measure the electric field, plasma waves

37 and radio waves for the first time in Mercury's plasma environment. The SCM consists of two low-
38 frequency orthogonal search coil sensors (LF-SC) measuring two components of the magnetic field
39 (0.1 Hz – 20 kHz) in the spacecraft spin plane, and a dual-band search coil sensor (DB-SC) picking
40 up the third component along the spin axis at both low-frequencies (LF: 0.1 Hz – 20 kHz) and high-
41 frequencies (HF: 10 kHz – 640 kHz). The DB-SC and the two LF-SC sensors form a tri-axial
42 configuration at the tip of a 4.6-m coilable mast (MAST-SC) extending from the spacecraft body, to
43 minimize artificial magnetic field contamination emitted by the spacecraft electronics. After the
44 successful launch of the spacecraft on 20 October 2018, an initial function check for the SCM was
45 conducted. The nominal function and performance of the sensors and preamplifiers were confirmed,
46 even with the MAST-SC being retracted and stowed in the spacecraft body, resulting in the detection
47 of large interference signals likely from spacecraft electronics. The MAST-SC is scheduled for
48 deployment after the Mercury orbit insertion of Mio in 2025, allowing the SCM to make the first
49 higher frequency measurements of magnetic fluctuations in the Hermean magnetosphere and
50 exosphere, and the local solar wind. These measurements will contribute to the investigation of
51 fundamental problems in the Hermean plasma environment, including turbulence, magnetic
52 reconnection, wave-particle interactions and particle acceleration.

53
54
55 **Keywords**

56 Search coil; Magnetic field fluctuation; Plasma wave; Radio wave; Mercury; Magnetosphere;
57 Exosphere; Mercury Magnetospheric Orbiter (MMO); Mio; BepiColombo; solar wind; turbulence

60 **1. Introduction**

61 As part of the BepiColombo mission to Mercury (Hayakawa et al., 2004; Yamakawa et al.,
62 2008; Benkhoff et al., 2010, this issue), the Plasma Wave Investigation (PWI) onboard the Mio
63 spacecraft (Mercury Magnetospheric Orbiter: MMO) (Murakami et al., this issue) will measure the
64 electric field, plasma waves, and radio waves for the first time in and around Mercury's
65 magnetosphere and exosphere (Kasaba et al., 2010; this issue). Among the PWI subsystems, the
66 search-coil magnetometers will measure the three components of the magnetic field fluctuations in
67 the frequency range of 0.1 Hz to 20 kHz (which is defined as a “low frequency range” in the present
68 paper) and one component in the range above 10 kHz up to 640 kHz (defined as a “high frequency
69 range”). The data will allow us to carry out the first studies of low and high frequency
70 electromagnetic waves and turbulence in different regions of the Hermean environment: bow shock,
71 magnetosheath, magnetopause, magnetotail and solar wind. Moreover, they will make it possible to
72 identify the processes of wave-particle interactions and energy dissipation when combined with the
73 electric field and the plasma data from the PWI and MPPE suites (Kasaba et al., this issue, Karlsson
74 et al., this issue; Saito et al., 2010).

75 The search coil magnetometers onboard Mio consist of low-frequency search coil sensors (LF-
76 SC) detecting two orthogonal components of the magnetic field (0.1 Hz – 20 kHz) in the spacecraft
77 spin plane, and a dual-band search coil sensor (DB-SC) picking up another component along the spin
78 axis at both low-frequencies (LF: 0.1 Hz – 20 kHz) and high-frequencies (HF: 10 kHz – 640 kHz).
79 The LF-SC and DB-SC sensors are installed on the tip of a long (4.6-m) coilable mast (MAST-SC)
80 extending from the spacecraft body, to minimize magnetic field contamination emitted by the
81 spacecraft electronics.

82 The search coil magnetometers will contribute to investigating various fundamental problems in
83 the Hermean plasma environment such as turbulence, magnetic reconnection, wave-particle
84 interactions and particle acceleration. Turbulence is a key process that allows transferring energy
85 over the spatial scales of a nonlinear system, a phenomenon referred to as the turbulent cascade.
86 Observations in the solar wind showed that this cascade can span a broad range of frequencies (or
87 scales) that cover the MHD range (often referred to as the inertial range), where dissipation is
88 thought to be negligible, down to the kinetic scales (sub-ion and electron ranges) where the
89 processes of dissipation become important (Sahraoui et al., 2009). Similar observations have been
90 made in the Hermean plasma environment, an example is shown in Figure 1 (Huang et al., 2020).
91 One can observe three ranges of frequencies characterized by power-law scaling and are separated
92 by spectral breaks that occur close to the gyrofrequency of protons and heavier ions (Na^+) (note that
93 other characteristic scales/frequencies could not have been estimated because of the lack of the
94 plasma data). The different power-law evidenced in the spectrum reflect the change in the nonlinear
95 dynamics: the shallow spectrum at the lowest frequencies with a scaling close to f^{-1} recalls the so-

96 called “energy containing scales” in solar wind turbulence (e.g., Sahraoui et al., 2020). It is followed
97 by the classical inertial range of MHD turbulence with a slope close to the Kolmogorov spectrum $f^{5/3}$.
98 The spectrum steepens further to $f^{2.6}$ above the proton gyrofrequency, which indicates the
99 transition to kinetic turbulence that has a scaling close to $f^{2.8}$ as frequently reported in solar wind
100 observations and numerical simulations (Sahraoui et al., 2010; Howes et al., 2011). Therefore, key
101 questions arise as to which plasma modes (e.g., whistler, kinetic Alfvén wave (KAW)) dominate the
102 cascade at the sub-ion scales and which processes are responsible for energy dissipation, thus
103 converting it into thermal (heating) or suprathermal (acceleration) particles. The investigation of
104 high frequency (small scale) turbulence is thus crucial to unravel the processes of turbulent energy
105 dissipation and particle energization in space plasmas. Numerous studies have investigated plasma
106 turbulence in planetary magnetospheres and the spatial evolution of its properties (e.g., magnetic
107 energy spectra, intermittency, energy dissipation rate, from the shock to the inner magnetosphere of
108 Jupiter (Tao et al., 2015), Saturn (Hadid et al., 2015), Mars (Ruhunusiri et al., 2017), Venus (Xiao et
109 al., 2018) and, more recently, Mercury (Huang et al., 2020)). However, most of those studies were
110 limited to large (MHD) scales because of the lack of high frequency measurements from the
111 magnetic field that would have allowed one to investigate the small (electron) scales (Figure 1).
112 This gap will be filled by the search-coil magnetometers onboard the Mio spacecraft (and by the
113 other instruments of PWD), which will provide the first ever measurements in the Hermean
114 environment of 3D magnetic field fluctuations in the frequency range between 0.1 Hz and 20kHz
115 thanks to the LF-SC and DB-SC (LF) instruments, and in the range between 10 kHz and 640 kHz for
116 the single component covered by the DB-SC (HF) instrument. Such measurements of higher
117 frequencies are expected to allow studying plasma turbulence down to the electron scales which
118 were not accessible to Messenger.

119 Another key process of particle energization in magnetized plasmas is magnetic reconnection.
120 In turbulent plasmas, current sheets (and other coherent structures) form as a consequence of the
121 nonlinear energy cascade from large to small scales. Thin current sheets were shown to form in
122 numerical simulations and were observed in-situ by spacecraft. Their size can range from ion to
123 electron scales (e.g., Perri et al., 2012). Measuring of such kinetic size current sheets and other
124 coherent structures and associated wave activity will be made possible by the search-coil data from
125 the LF-SC and DB-SC instruments. An example of measurement of intense whistler activity within
126 electron scale structures by the MMS/SCM instrument is shown in Figure 2 (Huang et al., 2018).

127 Studies of magnetic reconnection can be completed by identifying the nature of the high
128 frequency waves (e.g., whistler modes) that are responsible for the processes of wave-particle
129 interactions near the reconnection sites (ion and electron diffusion regions), as generally done in
130 reconnection studies in the Earth’s magnetosphere (e.g., Huang et al., 2012; Huang et al., 2017).
131 Furthermore, fast plasma flows generated by reconnection or the kinetic ballooning-interchange

132 instability and which propagate through the Earth's magnetotail are also associated with a strong
133 wave activity. Indeed, their propagation leads to the formation of sharp magnetic and density
134 gradients (the so-called "dipolarization front") that can generate intense whistler and lower-hybrid
135 waves (e. g. Breuillard et al., 2016; Sergeev et al., 2009). The latter, although being quasi-
136 electrostatic waves, have a strong compressional magnetic component which, coupled with electric
137 field measurements, allows one to estimate their phase speed (e.g., Le Contel et al., 2017). These
138 fast flows can dissipate while propagating toward the planet due to intense emissions of KAW
139 toward the auroral region (Chaston et al., 2012). Finally, electromagnetic and electrostatic solitary
140 waves associated with electron phase space density holes that move along the background magnetic
141 field were also detected in the vicinity of dipolarization fronts with 1-3 ms time scales (e. g.
142 Matsumoto et al., 1994; Andersson et al., 2009; Le Contel et al., 2017). Dipolarization fronts were
143 recently detected with a 10 s timescale in Mercury's magnetotail by MESSENGER (e.g. Sundberg,
144 2012) and were shown to be related to betatron and Fermi electron accelerations (e.g., Dewey 2017).
145 However, high-frequency electromagnetic measurements were not available to investigate the wave-
146 particle interactions. This gap will be filled by the Mio search coil magnetometers through the
147 measurement of high frequency magnetic fluctuations. In particular, the DB-SC instrument can
148 measure one component of the magnetic field fluctuations up to 640 kHz, which will allow covering
149 all the local characteristic frequencies of the plasma (e.g., plasma frequency, electron cyclotron
150 frequency). The high-frequency data from the DB-SC instrument will be also crucial to
151 investigating the processes of radio wave emissions (e.g., solar type-II and type-III radio bursts) and
152 mode conversion (from electrostatic to electromagnetic) predicted to occur near the plasma
153 frequency f_{pe} and its harmonics (Bale et al., 1999; Cairns et al. 2003).

154 Another problem that can be investigated by the search-coil magnetometers of Mio is whistler-
155 mode waves (e.g., chorus emissions), which were detected not only in the vicinity of Earth but also
156 inside other planetary magnetospheres such as those of Jupiter, Saturn, and Uranus (Kurth and
157 Gurnett, 1991), and were shown to play an important role in magnetized plasma dynamics through
158 wave-particle interactions. Even in small crustal magnetic fields of Mars, whistler-mode chorus
159 emissions were observed (Harada et al., 2016). In the complex magnetic fields around Mercury's
160 magnetosphere, whistler-mode waves are expected to exist, and may be responsible for particle
161 acceleration and precipitation down to Mercury's surface. The LF-SC and DB-SC data in
162 combination with electric field data from the PWI instrument (Kasaba et al., this issue) will make it
163 possible to measure wave polarizations, wave normal angles, Poynting vectors and phase velocities
164 for identifying the generation and propagation mechanisms of different types of waves in the low-
165 frequency range.

166 Finally, it is worth emphasizing that all these studies will be achieved across all the regions that
167 will be explored by the BepiColombo/Mio mission (bow shock, magnetosheath, magnetopause,

168 magnetotail and nearby solar wind).

169 The BepiColombo/Mio spacecraft was successfully launched on 20 October 2018 and is now in
170 cruise phase toward Mercury, integrated with the Mercury Planetary Orbiter (MPO) spacecraft
171 (Benkhoff et al., this issue, Murakami et al., this issue). During the near-Earth commissioning phase
172 (NECP) after the launch, an initial function check for the SCM was performed, where the nominal
173 functions and performance of the sensors and preamplifiers were confirmed even under large
174 magnetic interference from the spacecraft electronics due to the stowed configuration of the MAST-
175 SC during cruise to Mercury. The search coil sensors will be deployed with the full extension of the
176 MAST-SC after the insertion of the Mio spacecraft into orbit around Mercury in 2025.

177 To address the science targets described above, the search coil magnetometers onboard the Mio
178 spacecraft have been carefully designed, built and calibrated to provide optimum performance even
179 under a harsh thermal and radiation environment around Mercury. In this paper, the search coil
180 magnetometer instruments onboard the Mio spacecraft are described in detail. Section 2 explains the
181 hardware design of the LF-SC and DB-SC, followed by their electrical performance in Section 3.
182 Section 4 provides the results of the initial function check during the NECP campaign, and Section 5
183 concludes the paper.

184

185 **2. Hardware Design**

186 **2-1. Overall design**

187 The search coil magnetometers (SCM) onboard Mio consist of two low-frequency search coil
188 (LF-SC) sensors and one dual-band search coil (DB-SC) sensor, which form an orthogonal
189 configuration allowing us to measure the full vector of the magnetic field fluctuations. Each of the
190 two LF-SC sensors has a single solenoidal coil wound on a magnetic core, to detect the magnetic
191 field in the low-frequency range between 0.1 Hz and 20 kHz. The DB-SC is composed of two pairs
192 of solenoidal coils around a single magnetic core. Each pair is constituted of a primary winding
193 connected via the preamplifier to a secondary winding ensuring the feedback flux needed to stabilize
194 the response of the antenna (see also block diagram in Figure 5 and section 2.3). The two pairs are
195 separated by a mutual reducer that allow picking up a low-frequency component (0.1 Hz to 20 kHz)
196 and a high-frequency component (10 kHz to 640 kHz) separately (Coillot et al., 2010). The LF-SC
197 and the DB-SC sensors and associated electronics system were designed and developed jointly by
198 the Japanese and French teams, respectively, in close collaboration with each other. Both teams have
199 built and provided the search coil magnetometers successfully flown on many spacecraft; e.g.,
200 Geotail, Cassini, Cluster, MMS, Themis, and Arase (for a comprehensive list of search coils onboard
201 spacecraft, see Ozaki et al., 2018).

202 Figure 3 shows an illustration of the Mio spacecraft with electric field and magnetic field
203 sensors. The SCM sensors are located on the tip of a 4.6-m mast (MAST-SC) extending from the

204 lower deck of the spacecraft, to minimize magnetic field interference from the instruments and their
205 associated electronics on the spacecraft body. The two LF-SC sensors, B_α and B_β , are in the
206 spacecraft spin plane, whereas the DB-SC sensor, B_γ , is parallel to the spin axis. In the spacecraft
207 coordinate system marked as (X, Y, Z), two types of electric field sensors (32-m tip-to-tip long wire
208 booms), WPT and MEFISTO, extend from the lower deck of the spacecraft along the X and Y axes
209 in the spin plane, respectively, perpendicularly to the spin axis (+Z) (Karlsson et al., this issue). The
210 MAST-SC, also deployed from the lower deck, makes an angle of -45 degrees from the +X direction
211 in the spin plane. On the tip of the MAST-SC the two LF-SC sensors, B_α and B_β , are arranged to
212 point into the (+X) and ($-Y$) directions, while the DB-SC sensor, B_γ , points into the $-Z$ direction,
213 respectively, in the spacecraft coordinate system.

214 The detailed configuration of the SCM sensors and the MAST-SC is illustrated in Figure 4. A
215 set of tri-axial search coil sensors are placed on a top plate of an extendable mast, where the two
216 orthogonal LF-SC sensors in the spin plane are arranged by 45 degrees from the mast axis, while the
217 DB-SC sensor is perpendicular to them and directed along the spin axis. A 4.6-m coilable mast
218 extends from a canister installed on the side panel of the lower deck. Though not shown in the
219 figure, all the sensors on the top plate and the mast itself are covered with a thermal blanket to
220 protect them from a thermally harsh environment around Mercury. The signal outputs from the
221 sensors are connected through a wire harness to a preamplifier box (SC-Pre) mounted beside the
222 mast canister, which are both placed inside the temperature-controlled spacecraft body. A
223 temperature sensor is attached to the mast top plate, and a temperature sensor and a heater are
224 installed in the preamplifier box. Also shown in Figure 4b are the flight models of the SC-Pre, the
225 SCM sensors assembly (Figure 4c) and the MAST-SC in full extension during a ground test (Figure
226 4d).

227 Figure 5 shows a block diagram of the SCM sensors and preamplifiers. The low-frequency
228 voltages picked up by the two LF-SC sensors, B_α and B_β , are fed to two preamplifiers (LF-SC-Pre)
229 in the preamplifier box through a wire harness along the mast, and then transmitted to the two
230 magnetic field channels, B_x and B_y , of the EWO-WFC/OFA receiver (EWO-WFC/OFA(B)) for
231 waveform acquisition and their spectral analysis inside the PWI main electronics (PWI-E) (Kasaba
232 et al., this issue). The signals from the low- and high-frequency sensors of DB-SC are conveyed to
233 their respective preamplifiers (DB-SC-Pre) located also in the preamplifier box, where its low-
234 frequency signals go to the B_z channel of the EWO-WFC/OFA(B) receiver together with the LF-SC
235 signals, while its high-frequency signals are delivered to the magnetic field channel of the SORBET
236 receiver in PWI-E (Moncuquet et al., 2006). In the EWO-WFC/OFA(B) receiver the three low-
237 frequency magnetic field signals are first amplified (gain is 0 dB / 20 dB selectable) and band-
238 limited below a cut-off frequency of 20 kHz through an analog front-end circuit with 7th-order
239 elliptic low pass filters, and then digitally sampled at 65.536 kHz. A calibration signal is supplied by

240 the AM2P receiver in PWI-E to the low-frequency sensors, through the preamplifier box and the
241 wire harness (Trotignon et al., 2006). Another calibration signal is supplied by SORBET to the high-
242 frequency sensor of DB-SC. Feedback lines are connected from the preamplifier output to each of
243 the DB-SC sensor coils in order to give the negative magnetic feedback. The calibration signals are
244 applied to the sensors through their respective calibration coils. The overall power consumption of
245 the sensors and preamplifiers is 384 mW for nominal operation. All the preamplifiers are housed in
246 an aluminum box with thickness of at least 1 mm for protection against radiation.

247 Figure 6 presents the profiles of nominal sensitivities of the low-frequency and high-frequency
248 sensors and preamplifiers, and their typical dynamic ranges when combined with the EWO and
249 SORBET receivers. Also shown in the figure is a theoretical coverage in terms of spectral amplitude
250 and frequency of plasma and radio waves known from the terrestrial environment and scaled to
251 expected conditions in the Hermean magnetosphere and exosphere (Kasaba et al., this issue). For
252 the low frequency range, the dynamic range of 78 dB in spectral amplitude is controlled in the EWO
253 receiver by 0 dB and 20 dB gain steps. The high frequency signals have a dynamic range of 120 dB
254 provided by the SORBET receiver. The targeted plasma waves should be almost entirely covered by
255 the search coil's observable range. It is expected to cover as well the spin-modulated DC magnetic
256 field B_0 at 0.25 Hz (two components in the spin plane).

257 Table 1 summarizes the flight model specifications of LF-SC and DB-SC.

258

259 **2-2. Low-Frequency Search Coils (LF-SC)**

260 The low-frequency search coils have two identical sensors, each of which picks up a single
261 axial component of magnetic field. Figure 7a illustrates the structure of one axis sensor. The search
262 coil sensor consists of a high-permeability magnetic core, two solenoid coils wound on it, and an
263 electrostatic shield. The magnetic core is a 5 mm × 5 mm × 105 mm square bar composed of a
264 number of 5 mm × 105 mm permalloy sheets of 0.1mm thickness, which are laminated with
265 insulating adhesive to reduce the eddy current loss inside the core. The core is inserted into a plastic
266 bobbin on which a primary solenoid coil with 16,000 turns is wound. Also wound on the same
267 bobbin is a secondary coil of 20 turns used for applying a calibration signal to the sensor. The
268 primary and secondary coils are made of a polyimide-coated copper wire of 0.1-mm diameter. To
269 reduce the stray capacitance of the primary coil, the winding is divided into eight sections separated
270 with flanges (Dalessandro et al, 2007). The coils and core are covered with an aluminum chassis
271 that works as an electrostatic shield to reduce an electric field picked-up by the coil (Ozaki et al.,
272 2015). To prevent the eddy current flowing on the surface of the shield which significantly reduces
273 the magnetic flux inside the coil, a thin slit (gap) is put on each of the two opposite sides of the
274 shield. The shield is supported by flanges of the bobbin with screws and a potting material. The
275 bobbin is made of polyimide plastic, to withstand the harsh space environment. The picture of the

276 sensor (flight model) is shown in Figure 7b.

277 Figure 8 shows an equivalent circuit of the search coil sensor and preamplifier, which works as
278 an LCR circuit with the inductance L_C , the resistance R_C , and the stray capacitance C_C due to the coil
279 structure. The resistance R_{loss} includes the loss caused by the core, and C_{cable} is the capacitance of
280 the harness cable (shielded and twisted wires) between the sensor output and the preamplifier. The
281 sensor output signal is fed to a current-to-voltage (I-V converter) amplifier with a feedback
282 resistance R_F (Ozaki et al., 2014). Due to the existence of the capacitance, the impedance of the
283 sensor has a resonance frequency where the LC impedance goes to infinity, which is observed
284 around a few kHz for the LF-SC sensors. The current source induced by the magnetic flux gathered
285 by the core is picked up by the primary solenoid coil and is expressed as

$$I_C = \frac{V}{R_C + j\omega L_C}, V = j\omega\mu_{\text{eff}}NBS$$

286 where V is the induced voltage of the primary coil, B is the magnetic field to be measured, N is the
287 number of turns of the primary coil, S is the cross section of the core, and ω is the angular frequency.
288 The effective permeability μ_{eff} is given as a function of the core cross-section and length for a large
289 value of core initial permeability (Seran and Ferreau, 2005); $\mu_{\text{eff}} = 159$ for the permalloy core of 5
290 mm \times 5 mm \times 105 mm.

291 Two preamplifiers for the LF-SC sensors (LF-SC-Pre) are housed in the preamplifier box inside
292 the spacecraft. Figure 9 shows a block diagram of the LF-SC sensors and preamplifiers. Here we
293 adopted a preamplifier of current-to-voltage type (I-V converter) whose advantage is virtually to
294 short out the stray and cable capacitances so that a flat gain response is obtained around the
295 resonance frequency without any necessary feedback as in the conventional voltage amplifier.
296 Similar current-to-voltage amplifiers have been used in the search coil magnetometers onboard the
297 Arase satellite (Ozaki et al., 2018). The current-to-voltage amplifier is configured with a low-
298 current-noise FET amplifier, to minimize the current noise. To achieve the largest possible
299 dynamical range for the measurement, a second preamplifier for gain adjustment is put after the first
300 current-to-voltage preamplifier.

301 Another buffer amplifier is used to receive and supply a calibration signal to the calibration coil
302 of each sensor. The calibration signal is supplied from the AM2P receiver via the EWO board in
303 PWI-E, which consists of a sequence of swept-frequency digital sine waves generated by a
304 synthesizer (Kasaba et al., this issue; Trotignon et al., 2006). When received by the buffer amplifier,
305 the calibration signal is smoothed by a low-pass filter that eliminates the discontinuity in the digital
306 sine wave to create impulsive noises in the induced voltage on the primary coil due to the derivative
307 nature of the Faraday's law of induction. The same calibration signal is distributed to the two LF-SC
308 sensors, as well as to the low-frequency sensor of DB-SC, via the respective calibration coils.

309 The power supply (+12V) is filtered by an active low-pass filter to reduce high-frequency noise

310 and to improve the power supply rejection ratio (PSRR). The preamplifier circuit and its PCB layout
311 were carefully designed to reduce the internal crosstalk between B_α and B_β components.

312

313 **2-3. Dual-Band Search Coil (DB-SC)**

314 The DB-SC sensors cover two distinct frequency bands: LF (0.1 Hz – 20 kHz) and HF (10 kHz
315 – 640 kHz). The structure of DB-SC sensors is shown in Figure 10. On a single high-permeability
316 magnetic core (ferrite core with high Curie temperature $>200^\circ$ C), the DB-SC sensor carries two
317 separate sets of coils with a different number of windings to cover two different frequency ranges: a
318 large number of turns (15,000) for low-frequencies and less turns (400) for high-frequencies. The
319 two coils are separated by a mutual reducer which allows distinct measurements of the magnetic
320 fluctuations in the two different frequency ranges (Coillot et al. 2010). The output voltages from
321 these coils are applied to LF and HF preamplifiers (DB-SC-Pre).

322 The response of the instrument exhibits a resonance frequency that reduces its dynamic range.
323 This problem is solved by injecting the preamplifier response into a feedback winding in order to
324 flatten the transfer function. An advantage of this method is a transfer function that is insensitive to
325 temperature variations on its flat part. Similarly to the LF-SC sensors, the calibration signals of the
326 DB-SC (LF) will be delivered by the AM2P receiver via the EWO board whereas those of the DB-
327 SC (HF) will be delivered by the SORBET receiver (pseudo-random-noise pulses). These
328 calibration signals will be injected to the corresponding feedback windings. In-flight calibration
329 achieves two goals, first to verify the optimal functioning of the instrument, and second to enable an
330 estimate of the transfer functions and track any changes in time.

331 The electronics components used to achieve the low noise, low power consumption and
332 wideband preamplifier have a long heritage since they have been used on previous missions such as
333 Cassini (Gurnett et al., 2004), Cluster (Cornilleau-Wehrin et al., 1997, 2003), THEMIS (Roux et al.,
334 2008; Le Contel et al., 2008) and MMS (Le Contel et al., 2016). The preamplifiers were integrated
335 into a 3D+ Technology. The components were plugged on a common PCB together with LF-SC-Pre
336 in order to save mass and volume.

337 The main characteristics of this instrument are a broadband frequency measurement, with a
338 physical length of 111 mm ~~length~~ (100 mm for the sensor and 11 mm for the extra length of the
339 mechanical interface) and a mass of 65 g (which includes ~10 cm cable length), and a very low
340 **sensitivity: closer to the values of LF-SC in the frequency range from 1 Hz to 10 kHz for DB-SC**
341 **(LF) (see Table 1) and below 30 fT/Hz^{1/2} in the frequency range from 20 to 200 kHz for DB-SC**
342 **(HF)** and the possibility of in-flight calibration. The signals between the sensors and preamplifiers
343 are transmitted by shielded and twisted wires. The LF and HF signals are to be fed to the EWO and
344 SORBET receivers, respectively (Kasaba et al., this issue; Moncuquet et al., 2006).

345

346 **2-4. MAST-SC**

347 The tri-axial structure of the search coil sensors (SC assembly) is installed on the tip of MAST-
348 SC. Before extension, the mast structure shown in Figure 4 is wound into a compact coil shape and
349 stowed in a canister. Such a “coilable” mast structure has been successfully used onboard several
350 spacecraft (e.g., Geotail (Kokubun et al., 1994), Nozomi (Yamamoto and Matsuoka, 1998), Kaguya
351 (Tsunakawa et al., 2010) and Arase (Ozaki et al., 2018; Matsuoka et al., 2018)). It allows keeping
352 the sensitive (DC and AC) magnetometers away from the body of the spacecraft, and thus
353 minimizing interference from the spacecraft electronics. The advantages of the coilable mast
354 structure are its low mass and small volume in retracted configuration, and an accurate attitude of
355 tip-mounted sensors (within several degrees achievable) with a long length of extension (12 meters
356 for the case of Kaguya (Tsunakawa et al., 2010)). During the extension of the mast, the coil
357 structure is slowly unwound and released by an electric motor inside the canister, which lets the mast
358 extend outward due to a restorative force of each of the three longerons back to a straight wire. In a
359 fully extended configuration as illustrated in Figure 4, the three straight longerons in parallel are
360 supported by radial spacers. The harness wires between the sensors and preamplifiers are put along
361 the three longerons.

362 As is shown in Figure 4, the two LF-SC sensors and one DB-SC sensor are orthogonally
363 arranged by a supporting structure made of polyimide plastic. The whole tri-axial configuration of
364 the sensors is constructed on a circular top plate made of carbon fiber reinforced plastic (CFRP) that
365 has a large impedance so that no eddy current loss is expected there. Not shown in the figure, the
366 sensor assembly is covered with a thermal blanket box, whereas the whole mast is covered with a
367 thermal blanket called a "boot" to withstand the harsh thermal environment around Mercury. The
368 thermal blankets are made of multi-layered insulator (MLI).

369 The top plate is attached perpendicularly to the mast axis on which the pointing accuracy of the
370 sensors is kept within 6 degrees when the mast is fully extended, as measured by a ground test (see
371 Figure 4d). Though the inaccuracy of the sensor’s pointing direction could cause small uncertainties
372 (up to 6 degrees) in wave propagation analysis of the measurement, the misalignment could be
373 corrected by estimating the actual attitude of the sensors based on the spin modulation of the DC
374 magnetic field measured by the search coils around Mercury (see Section 5). The mass of the whole
375 MAST-SC structure is 4.36 kg, including search-coil sensors and thermal blankets. The temperature
376 on the top plate is monitored by a temperature sensor for house keeping. Even inside the thermal
377 blanket the expected temperatures at the top plate will range from -55° C during the cruise phase to
378 +200° C at Mercury’s orbit, over which the sensor will be turned on. All equipment including the
379 mast and sensor structures were designed to be tolerant in such a severely wide temperature range.
380 From the viewpoint of measurement by the search coil sensors, their transfer functions were
381 measured in the ground thermal test for a temperature range between -55° C to +200° C. A few dB

382 difference in the modulus and several degrees in the phase of the transfer functions in this
383 temperature range were observed, compared with those shown in Figures 11 and 12 obtained at room
384 temperature. By monitoring the temperature of the sensors as well as performing the onboard
385 calibration, we will be able to compensate (calibrate) the temperature dependence to determine the
386 actual transfer functions of the sensors during the cruise phase as well as around Mercury.

387

388 **3. Electrical Characteristics**

389 **3-1. Low-Frequency Search Coils (LF-SC)**

390 Figure 11 shows the frequency characteristics of gain, phase and sensitivity of the α -axis sensor
391 of LF-SC measured on the ground before launch, which are similar to those for the β -axis sensor
392 (not shown here). Figure 11a is the frequency characteristics of the gain, which is defined as the
393 modulus of the transfer function from “the magnetic field picked up by the sensor” to “the voltage
394 output by the preamplifier.” An approximately flat gain is achieved between 500 Hz and 2 kHz
395 (around a resonance frequency of a few kHz) by the current-to-voltage amplifier without the
396 conventional feedback coil. The frequency characteristics of the phase of the transfer function is
397 shown in Figure 11b. The sensitivity of the search coil is defined as a noise-equivalent magnetic
398 induction (NEMI), which includes all the noise sources in the sensor and the preamplifiers. The
399 NEMI is plotted in Figure 11c, which is almost compliant with the nominal sensitivity illustrated in
400 Figure 6.

401

402 **3-2. Dual-Band Search Coil (DB-SC)**

403 Figure 12 presents the gain and phase profiles of DB-SC for the low-frequency sensor and the
404 high-frequency sensor measured on the ground. The low-frequency profiles of the DB-SC gain and
405 phase (Figures 12a and 12b) are similar, but not identical, to those of LF-SC. The high-frequency
406 gain (Figure 12c) includes the gain of the SORBET receiver (see Moncuquet et al., 2006; Kasaba et
407 al., this issue).

408 The resulting noise floor of the DB-SC sensors and preamplifiers is shown in Figure 13. Note
409 that this noise floor (e.g., 5×10^{-5} nT/Hz^{-1/2} at 1 kHz for DB-SC) is higher than that of the Cluster
410 search-coil (e.g., 1.7×10^{-5} nT/Hz^{-1/2} at 1 kHz for Cluster), because the latter has longer sensors (27
411 cm to be compared with the 10 cm of the LF-SC and DB-SC). However, the instrument will be
412 sensitive enough to capture the magnetic field fluctuations in the Hermean environment, including
413 the solar wind at 0.3 AU, which have higher amplitudes than those at 1AU (Sahraoui et al., 2011).

414 The low-frequency magnetic field signals from the LF-SC and DB-SC are fed to the EWO
415 receiver, where the signals are band-limited through a 7th-order elliptic low-pass filter with a flat
416 transfer function below a cut-off frequency of 20 kHz (Kasaba et al., this issue).

417

418 **4. In-flight performance of the Search Coil Sensors: Near-Earth commissioning phase**

419 After the successful launch of BepiColombo in October 2018, a Near-Earth Commissioning
 420 Phase (NECP) campaign was carried out in November, 2018, to confirm initially the nominal
 421 functioning of the onboard instruments. During the NECP campaign, most of the electronics parts of
 422 PWI were turned on and preliminary electric field and magnetic field data were acquired.

423 During the cruise phase the Mio spacecraft is positioned inside the sunshield (MOSIF) and
 424 integrated with the Mercury Planetary Orbiter (MPO) spacecraft (Milillo et al., 2010; this issue) and
 425 the Mercury Transfer Module (MTM) (Benkhoff, et al., this issue). Neither electric field sensors nor
 426 magnetic field sensors will be deployed until the separation of Mio from MPO after the Mercury
 427 orbit insertion scheduled in December 2025. Before the extension of MAST-SC, the search coil
 428 magnetometers will be kept outside the side panel of Mio on the retracted mast stowed in the canister.
 429 The SC sensors are thus expected to be subject to magnetic interference from the spacecraft
 430 electronics and its instruments.

431 For the low-frequency magnetic field measurement by the EWO receiver during the NECP
 432 campaign, only the dynamic spectral intensity of voltage, $|V| = \sqrt{V_x^2 + V_y^2 + V_z^2}$, was transmitted to
 433 the ground, where V_x , V_y and V_z are the voltage spectral intensities calculated onboard using the
 434 voltage waveforms measured in the B_x , B_y and B_z channels of the EWO-WFC/OFA(B) receiver.
 435 The voltage spectral intensities are obtained as $V_x = G_\alpha B_\alpha$, $V_y = G_\beta B_\beta$ and $V_z = G_\gamma B_\gamma$, where G_α , G_β
 436 and G_γ are the corresponding gains that include the sensors, the preamplifiers and the EWO
 437 electronics, and B_α , B_β and B_γ are the spectral intensities of magnetic field picked up by the LF-SC
 438 sensors (α and β) and the DB-SC (LF) sensor (γ). It is not possible to exactly convert the measured

439 voltage spectra, $|V| = \sqrt{G_\alpha^2 B_\alpha^2 + G_\beta^2 B_\beta^2 + G_\gamma^2 B_\gamma^2}$, back into the magnetic field spectra, $|B| =$

440 $\sqrt{B_\alpha^2 + B_\beta^2 + B_\gamma^2}$, since the gain profiles for the LF-SC (G_α, G_β) and for the DB-SC (LF) (G_γ) are

441 not identical (see Figures 11 and 12). Here, we approximately calculated the magnetic field spectra
 442 using the “noise gain” calculated as $G_n \equiv |V_n|/|B_n|$, which is the noise voltage at the EWO output,

443 $|V_n| = \sqrt{V_{nx}^2 + V_{ny}^2 + V_{nz}^2} = \sqrt{G_\alpha^2 B_{n\alpha}^2 + G_\beta^2 B_{n\beta}^2 + G_\gamma^2 B_{n\gamma}^2}$, divided by the noise-equivalent magnetic

444 induction (NEMI) at the sensors, $|B_n| = \sqrt{B_{n\alpha}^2 + B_{n\beta}^2 + B_{n\gamma}^2}$, where (V_{nx}, V_{ny}, V_{nz}) and

445 $(B_{n\alpha}, B_{n\beta}, B_{n\gamma})$ are the noise voltages expected to appear at the three channels of the EWO output
 446 and the three components of NEMI measured on the ground (see Figures 11 and 13), respectively.
 447 The noise gain should be accurately applied for evaluating the onboard noise levels (NEMI) of the
 448 sensors (see below).

449 Figure 14a shows the dynamic spectra of magnetic field $|B|$ during 01:00–02:00 UT on

450 November 10, 2018, measured in the frequency range between 64 Hz and 20 kHz. The
451 monochromatic tones appearing around 200–300 Hz, 1.5 kHz, 4 kHz and 9 kHz, and the quasi-
452 periodic wideband impulses below 10 kHz are, most likely, due to interference from some
453 instruments onboard Mio, which remain to be identified.

454 Next, we evaluate the noise levels of the search coil magnetometers measured in space during
455 the NECP campaign. Although contaminated with large magnetic interferences for most of the time
456 as seen in Figure 14a, the observed spectra occasionally decreased down to the “quiet” values which
457 might coincide with the noise-equivalent magnetic induction (NEMI) which represents the
458 sensitivity of the search coil sensors. The frequency spectra of magnetic field calculated in such a
459 way is plotted in Figure 14b, where the magnetic field spectrum averaged over the time period (one
460 hour in Figure 14a) is shown with a red curve. In black is plotted the minimum value of magnetic
461 field at each frequency bin observed during the same time period. These “quiet” values in the
462 spectrum agreed well with the NEMI values $|B_n|$, especially in the frequency ranges of 700 Hz to
463 1.2 kHz and above 5 kHz. It is remarkable that, even not deployed, the NEMI measured in-flight
464 agrees relatively well with the one measured on the ground.

465 It is worth recalling that the magnetic field intensities $|B|$ presented here were obtained from
466 the combined (over the three components) voltage $|V|$ in a noisy environment as explained above.
467 Further validation of the performance for each sensor separately will be achieved after the final
468 insertion into Mercury orbit in 2025.

469 Figure 15 shows a result of the onboard calibration of the low-frequency sensors carried out on
470 the same day. Supplying the swept-frequency calibration signals provided by AM2P through the
471 EWO to the three low-frequency sensors via their respective calibration coils, we can obtain the
472 transfer functions (i.e., calibration gains) of the sensors. The symbols represent the gain and phase
473 of the transfer functions obtained onboard Mio, whereas the blue lines show the corresponding
474 profiles measured during testing on the ground before launch. An excellent agreement was obtained
475 between the onboard and ground profiles. One can note that the shape of the calibration gains in
476 Figure 15 is a little bit different from those in Figures 11a and 12a, because the calibration gain
477 includes effects of the calibration buffer amplifier with a low-pass filter as explained in Section 2.2.

478 These results validate and demonstrate the healthy functioning of the sensors and preamplifiers
479 of LF-SC and DB-SC (LF), as well as the EWO and AM2P receivers onboard Mio.

480 Regarding the DB-SC (HF) sensor, several tests were performed, confirming the nominal
481 functioning of the instruments with the SORBET receiver. An example is shown in Figure 16, which
482 presents the SORBET spectrogram of DB-SC data obtained during NECP, where the transfer
483 function of DB-SC has not been included yet. The spectrogram was computed over 4 successive
484 frequency bands (see Figure 12c), each of which has a distinct automatic gain control (AGC) (AGC
485 allows one to have a larger dynamical range of ~120dB (Moncuquet et al., 2006, Kasaba et al., this

486 issue)). Each frequency band has 32 logarithmically spaced channels, resulting in a total of 128
487 frequencies from 2.5 kHz to 620 kHz (central frequencies in the lowest and highest frequency bins
488 of SORBET). As mentioned above, the LF-SC and DB-SC were not deployed during NECP.
489 Therefore, most of the observed power in Figure 16 is likely to reflect interference from the
490 spacecraft body and/or its instruments. This should be the case for the frequencies 90 kHz and 180
491 kHz where spikes are detected.

492

493 **5. Summary**

494 The SCM instrument onboard Mio consisting of LF-SC and DB-SC sensors and preamplifiers,
495 was carefully designed and tested with the PWI, to detect the low-frequency magnetic vector field
496 (0.1 Hz – 20 kHz) as well as the high-frequency magnetic field along the spacecraft spin axis (10
497 kHz – 640 kHz). In a series of commissioning tests conducted during the NECP campaign after
498 launch, it was confirmed that the SCM worked well even on the retracted MAST-SC under a
499 magnetically noisy environment due to the spacecraft electronics. After the Mercury orbit insertion
500 in 2025, the MAST-SC will be fully deployed. The SCM will then make the first accurate
501 measurements of magnetic fluctuations in Mercury’s magnetosphere, exosphere, and in the nearby
502 solar wind, and contribute to the understanding of plasma dynamics in those environments.

503 Once in orbit around Mercury, the Mio spacecraft will be spinning at the spin period of 4 sec.
504 The spin motion will create a sinusoidal signal at 0.25 Hz of the DC magnetic field in the LF-SC
505 sensors in the spin plane, whereas a much weaker modulation might be observed by the DB-SC
506 sensor along the spin axis due to its possible misalignment with respect to the spin axis. Cross-
507 calibration of SCM spin-modulated signals with simultaneous observations from the flux gate
508 sensors (MGF) (Baumjohann et al., 2010; this issue) will improve estimates for the true attitude
509 (pointing directions) of all search coil sensors. Furthermore, cross-calibration of the two sensors in
510 their overlapping frequency range will allow to check the gain of each sensor.

511 The SCM will turn ON during the flybys at Earth, Venus and Mercury before the final insertion
512 into orbit around Mercury in 2025, which gives us an opportunity to potentially measure the
513 magnetic fluctuations in those environments. Even under a noisy environment on the retracted
514 MAST-SC, we expect that the SCM will be able to pick up high amplitude plasma and radio waves
515 during those flybys.

516

517

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525

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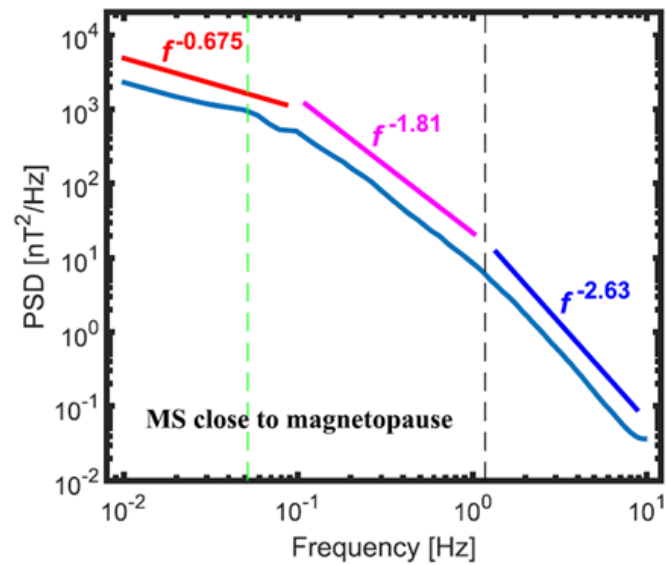
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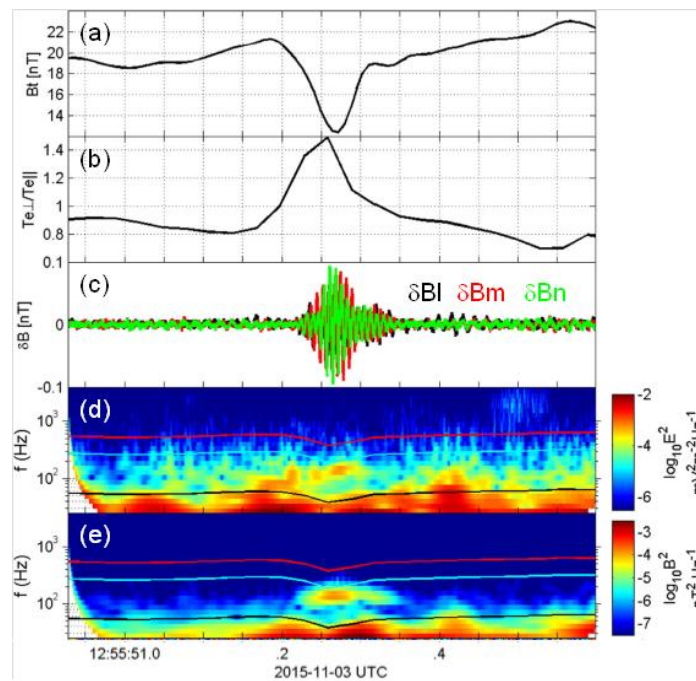
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730 **Figure 1: A magnetic energy spectrum measured by Messenger/MAG instruments in the**
731 **Hermean magnetosheath (MS) close to the magnetopause. Three spectral bands with different**
732 **power-law fits are evidenced. The vertical dashed line indicates the local ion gyrofrequency.**
733 **Proton and Na⁺ gyrofrequencies are marked by black and green dashed lines, respectively.**
734 **Adapted from Huang et al. (2020).**

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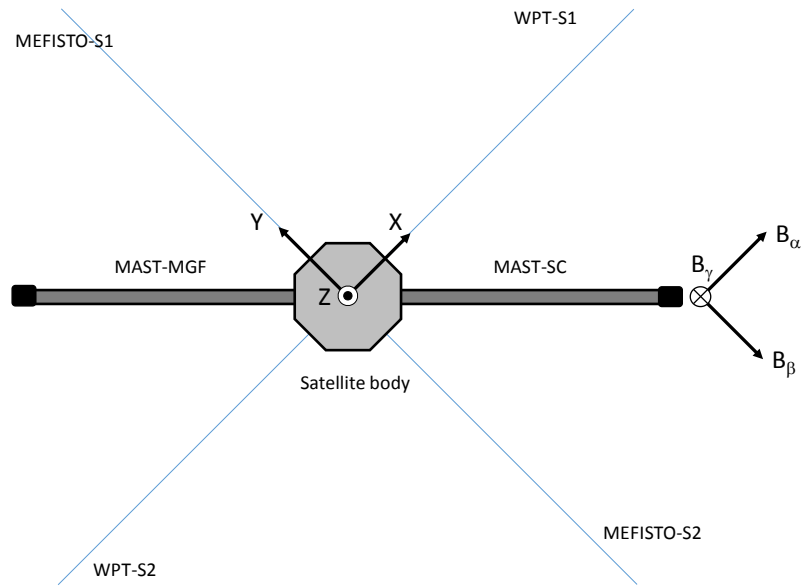
739 **Figure 2:** Example of the observations of whistler waves inside an electron vortex magnetic
740 **hole** on 2015 November 3 by the MMS spacecraft in the magnetosheath. (a) Magnetic field
741 strength; (b) the ratios between electron perpendicular temperature and parallel temperature;
742 (c) filtered magnetic field fluctuations from the SCM instrument; (d)–(e) power spectral
743 densities of the electric and magnetic components of the waves. The black, cyan, and red
744 curves in (d)–(e) indicate the frequencies $0.1 f_{ce}$, $0.5 f_{ce}$, and $1.0 f_{ce}$, respectively (f_{ce} is the
745 electron gyrofrequency). Similar studies can be achieved in the Hermean environment using
746 the LF-SC and DB-SC instruments onboard BepiColombo/MIO. Adapted from Huang et al.
747 (2018).
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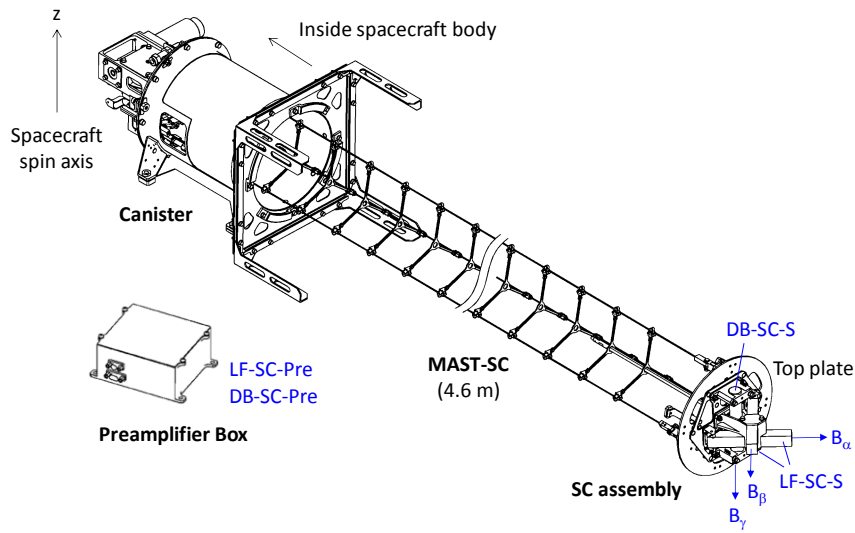
752 **Figure 3: Configuration of electric and magnetic field sensors onboard the Mio spacecraft.**
753 **The search coil sensors are placed on the tip of a 4.6-m mast extending from the spacecraft**
754 **body. Another mast is deployed from the opposite side of the spacecraft for the DC magnetic**
755 **field sensors (MGF) (Baumjohann et al., 2010; this issue).**

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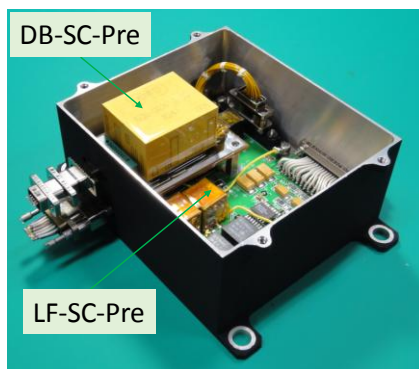
764 **Figure 4: Configuration of the search coil sensors and the extendable mast.** (a) An illustration
 765 **of the sensors on top of a coilable mast extending from the canister.** (b) The preamplifier box
 766 **with the top panel opened.** (c) The search coil sensors assembly on the mast top plate.
 767 **fully extended mast system during a ground test, with the search coil sensors located at the**
 768 **mast's tip.**



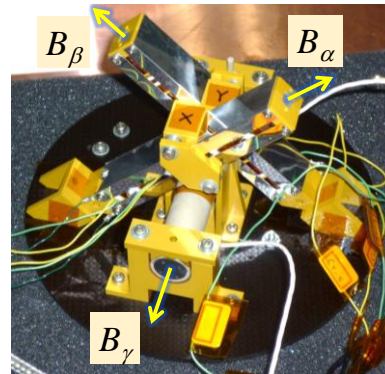
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(a)



(b)



(c)

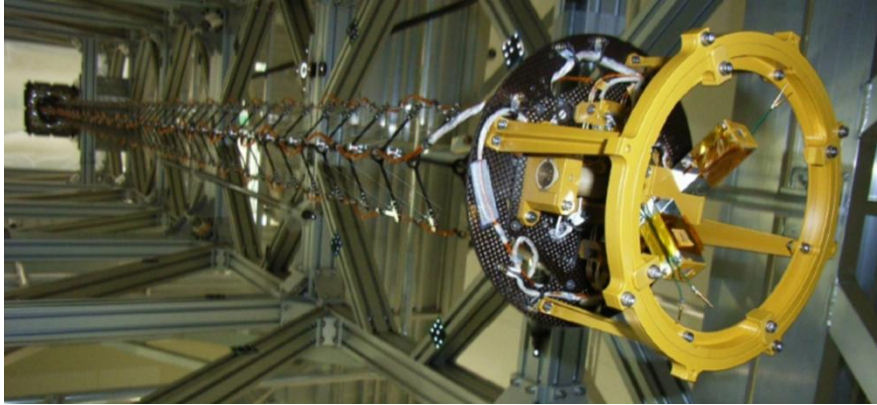
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774 **Figure 4 (continued)**

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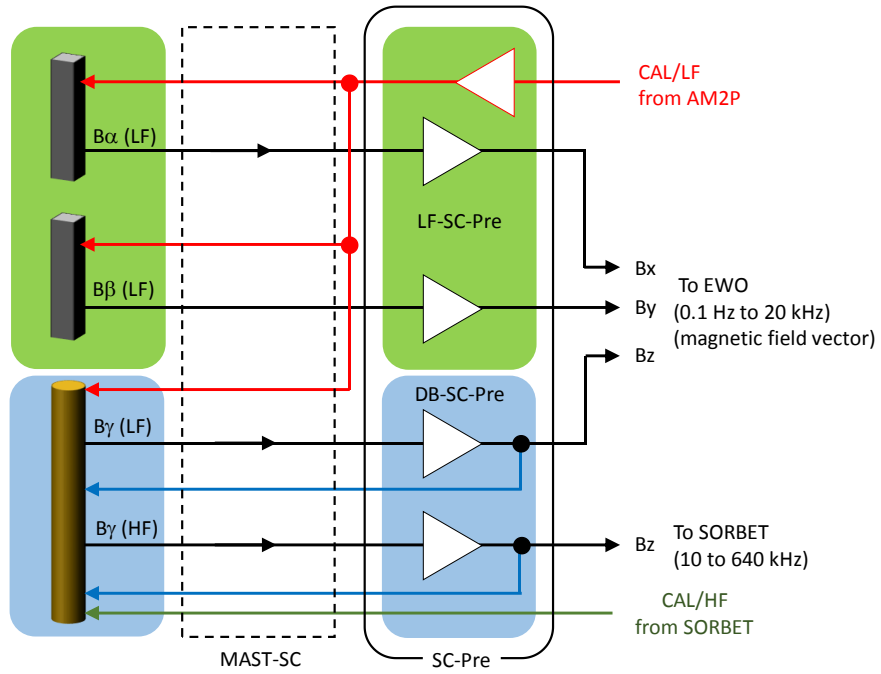
(d)

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780 **Figure 5: Block diagram of the search coil sensors and preamplifiers**

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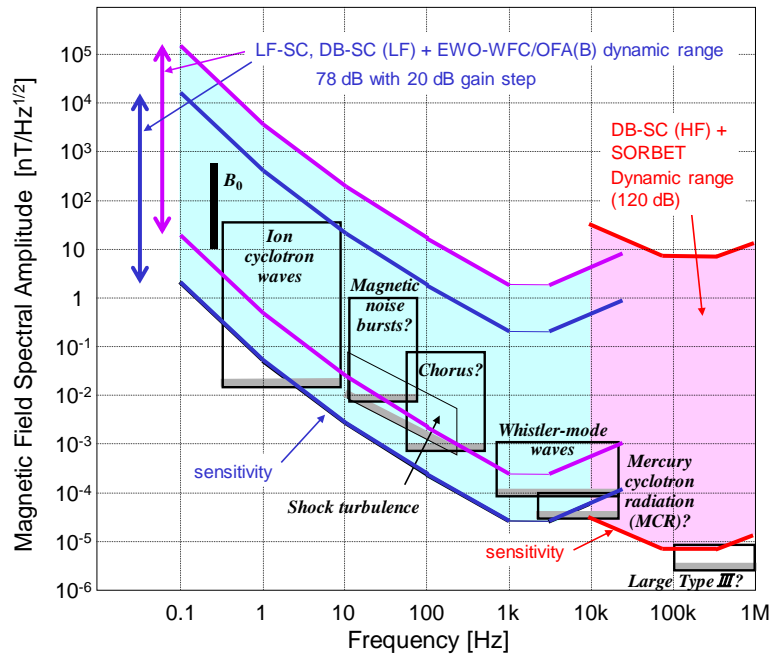


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784 **Figure 6: Sensitivities and dynamic ranges of search coil magnetometers combined with the**
 785 **EWO-WFC/OFA(B) and SORBET receivers. Also shown are the expected plasma and radio**
 786 **waves with spectral amplitudes corresponding to measurements in the terrestrial environment**
 787 **(Kasaba et al., this issue). The B_0 means the spin-modulated DC magnetic field to be measured**
 788 **around Mercury.**

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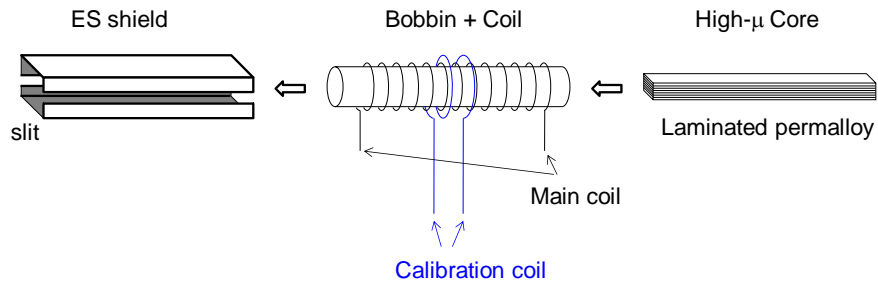
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792 **Figure 7: One axis sensor of LF-SC. (a) Structure and (b) the flight model of the one axis**
793 **sensor.**

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(a)



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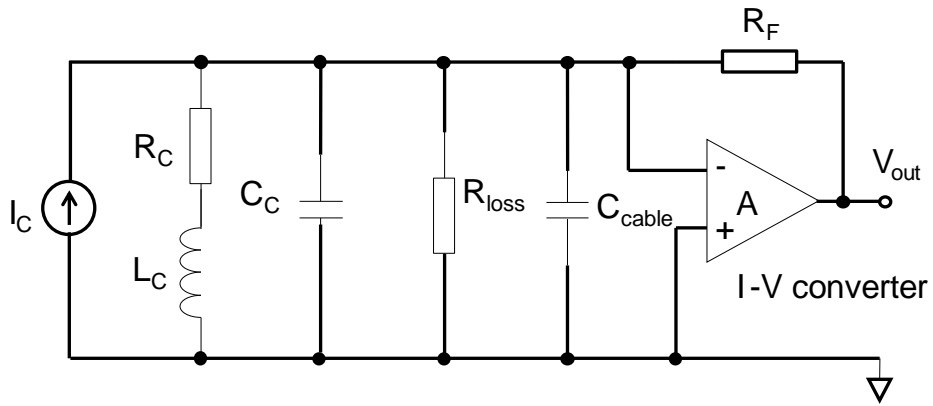
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(b)

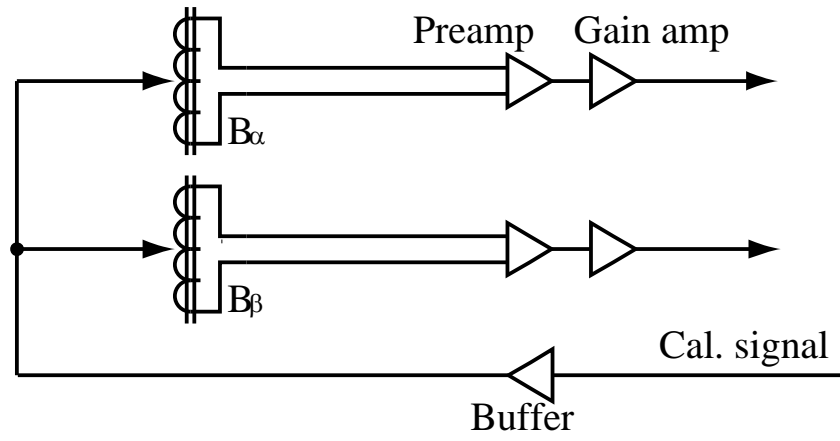
802 **Figure 8: Equivalent circuit of the LF-SC sensor. For the meaning of the labels beside the**
803 **circuit elements, refer to the text.**
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807 **Figure 9: Block diagram of the LF-SC sensors and preamplifiers.**

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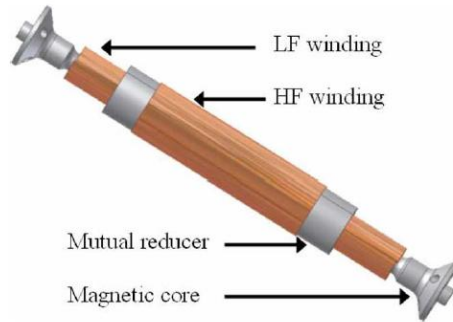


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811 **Figure 10: Structure of the DB-SC LF and HF sensors.**

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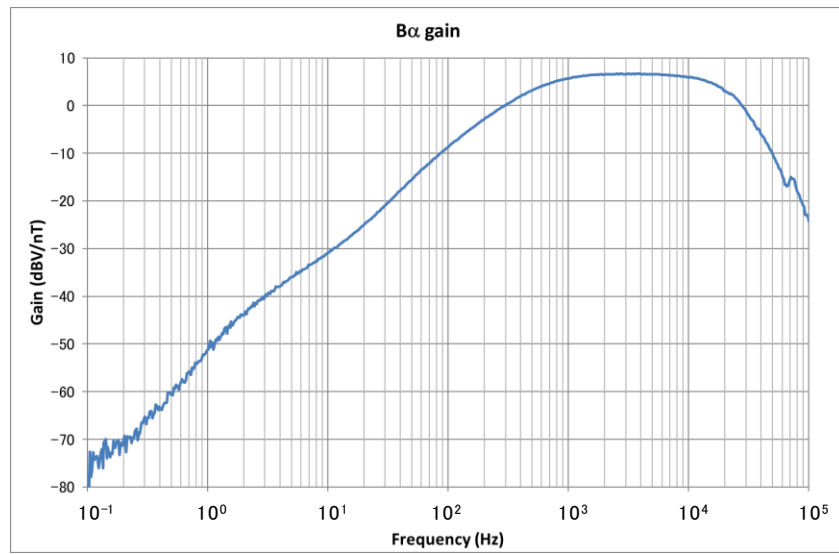
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816 **Figure 11: Gain, phase and sensitivity of the LF-SC measured on ground. Frequency**
817 **characteristics of (a) gain, (b) phase and (c) noise floor (noise-equivalent magnetic induction:**
818 **NEMI).**

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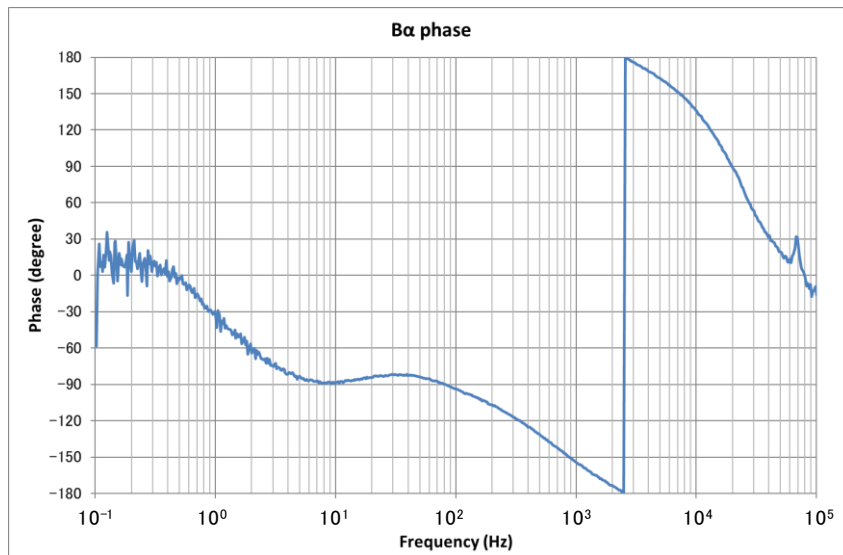
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(a)



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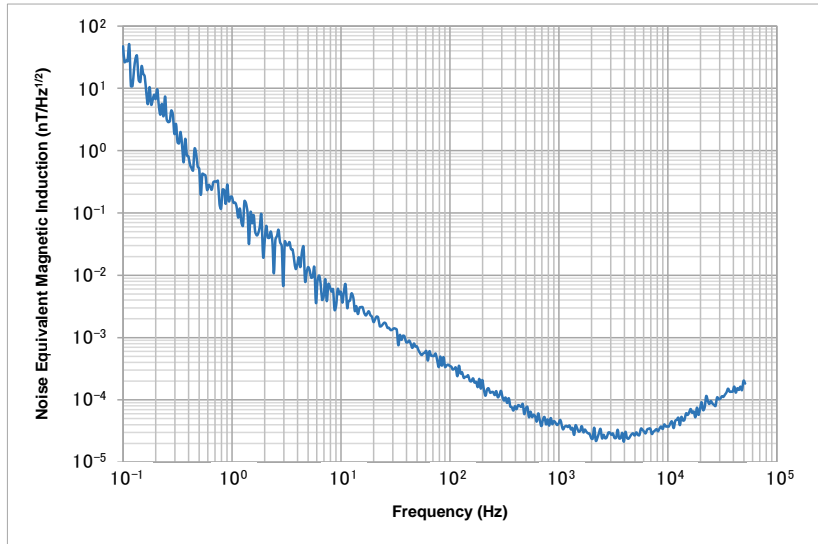
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(b)

826 **Figure 11 (continued)**

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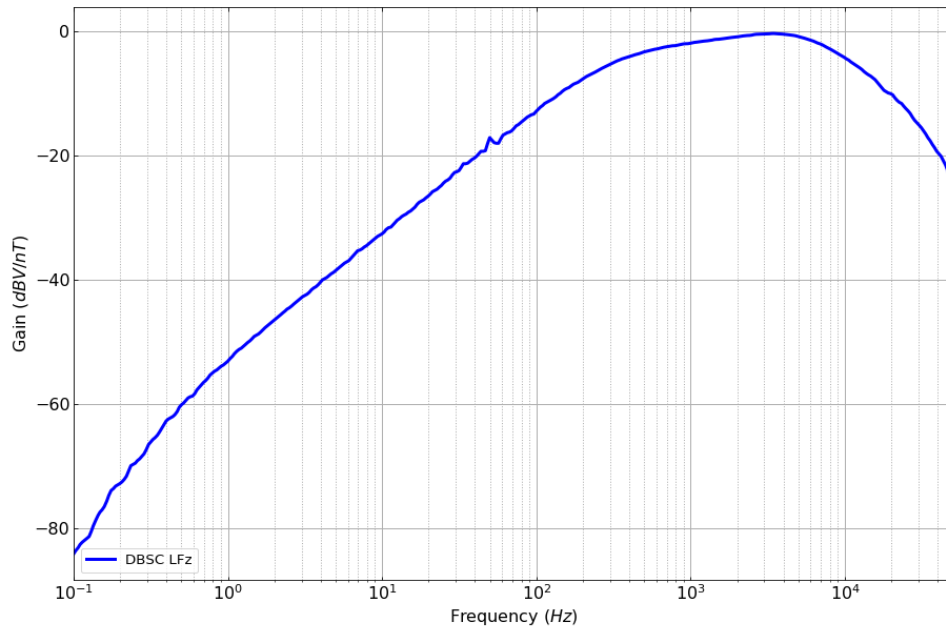
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(c)

831 **Figure 12: (a) Gain and (b) phase of DB-SC (LF) and (c) gain and (d) phase of DB-SC (HF)**
832 **measured on the ground.**

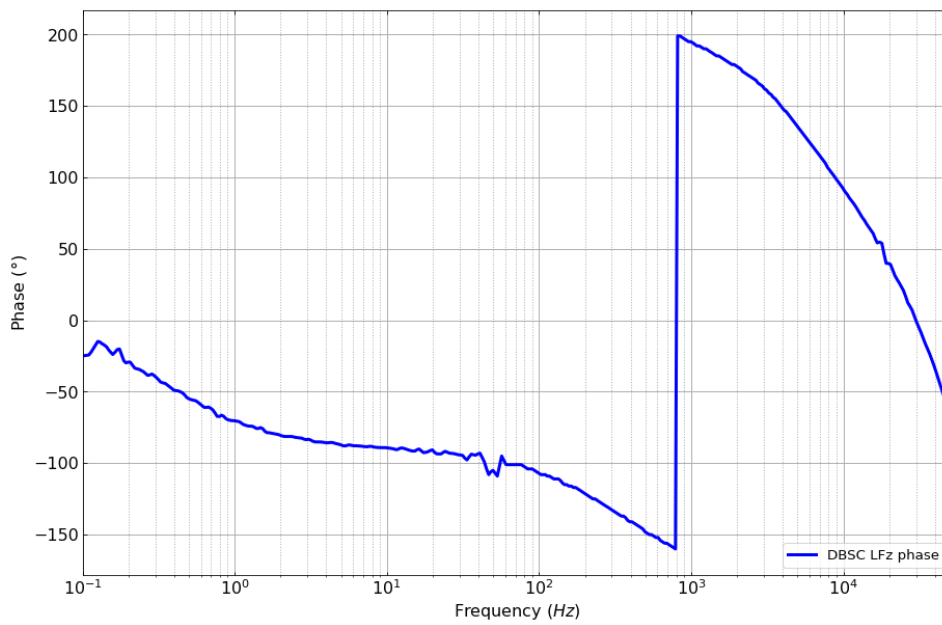
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(a)



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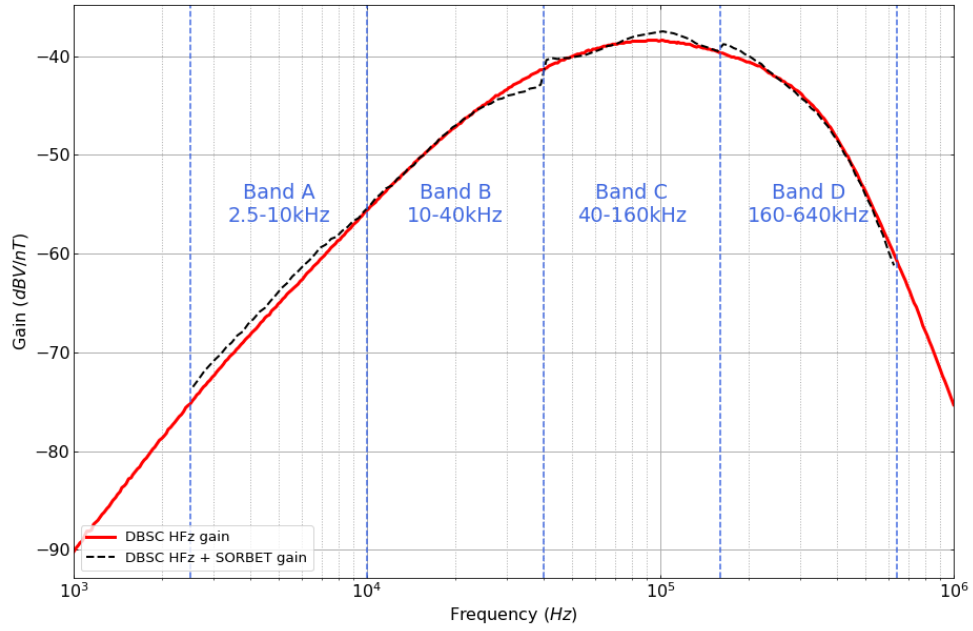
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(b)

839 **Figure 12: (continued)**

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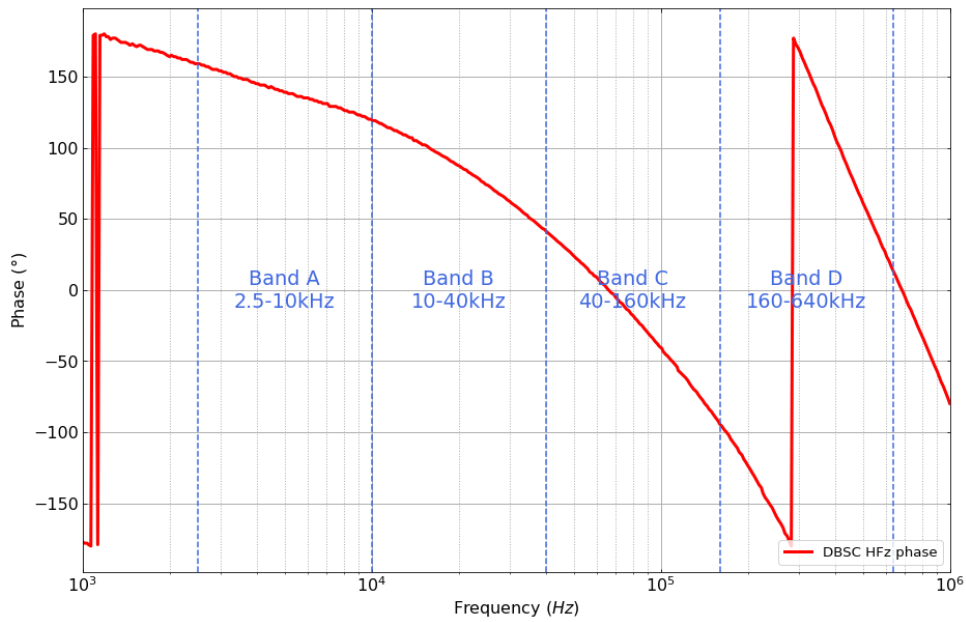


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(c)



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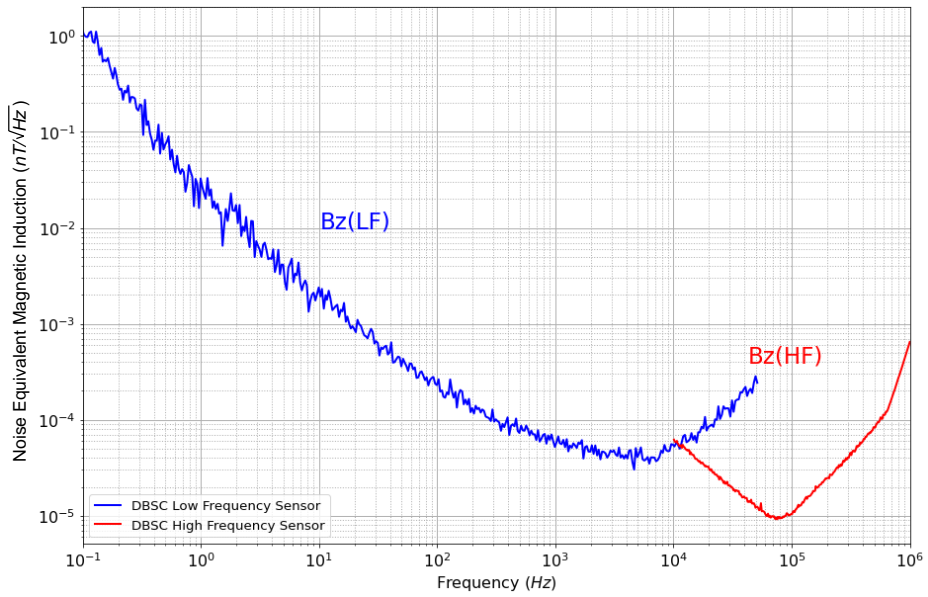
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(d)

848 **Figure 13: Noise floor (noise-equivalent magnetic induction: NEMI) of the DBSC (LF and HF)**
849 **sensor and electronics measured on the ground.**

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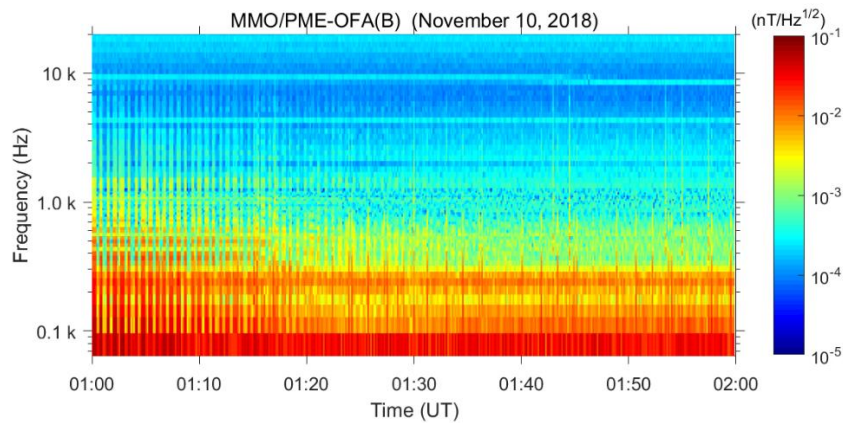


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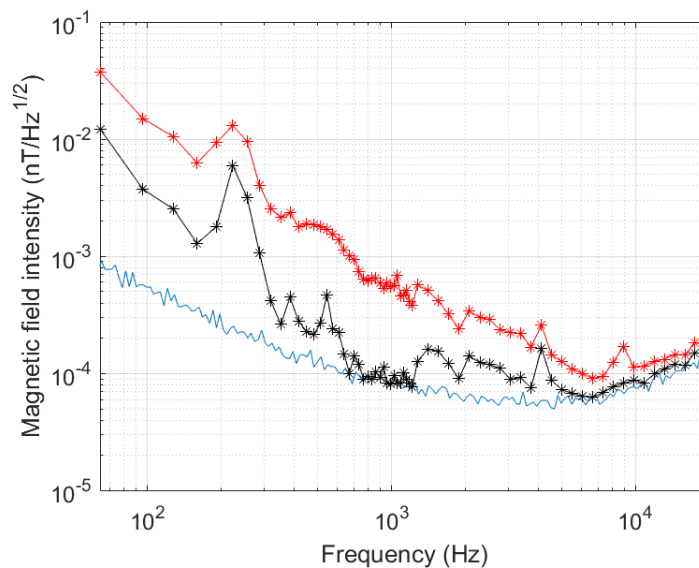
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854 **Figure 14: In-flight EWO data for low-frequency magnetic field during 01:00–02:00 UT on**
 855 **November 10, 2018, in the NECP campaign. (a) The dynamic spectra of $|B|$ converted using**
 856 **the noise gain for the three channels (see the text). (b) The frequency characteristics of**
 857 **magnetic field spectral amplitude: the red symbols show the profile averaged over the one hour**
 858 **in (a), while the black symbols plot the minimum value at each frequency bin observed in the**
 859 **same period. The blue curve is the noise spectrum of NEMI measured on the ground.**
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(a)

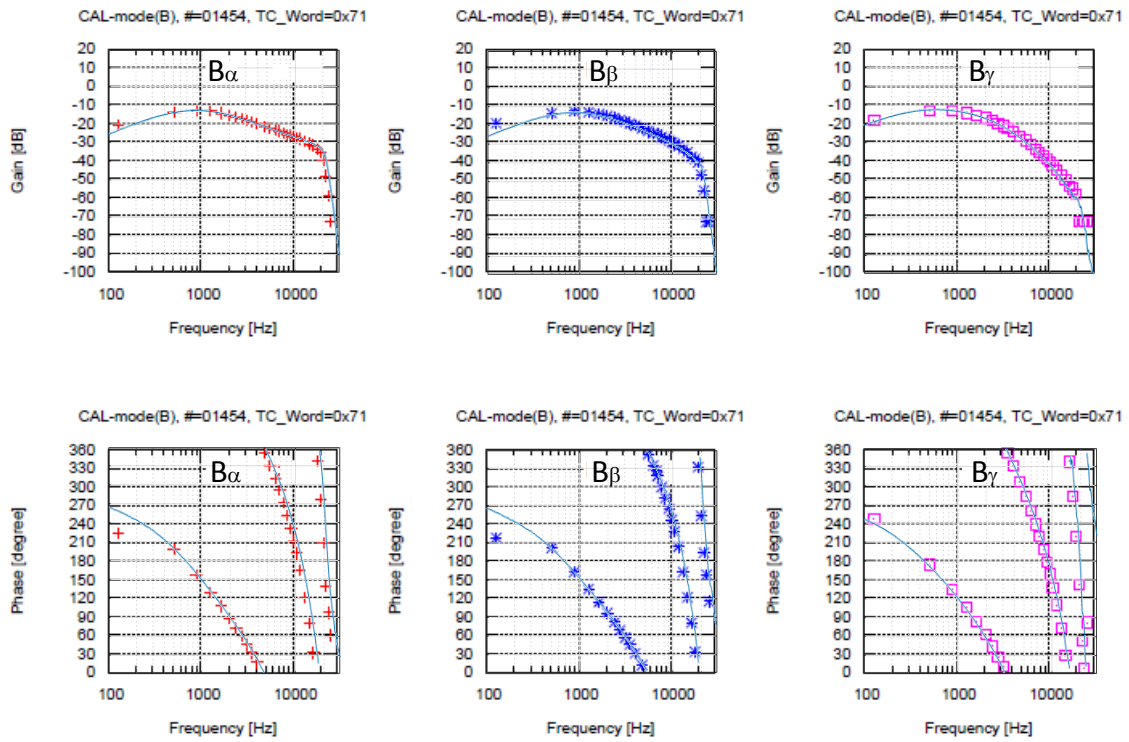


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(b)

865 **Figure 15: An in-flight calibration of the low-frequency sensors carried out on November 10,**
866 **2018 during NECP. The symbols represent the gain and phase of the transfer functions for the**
867 **three sensors obtained by the onboard calibration. The blue lines show the profiles measured**
868 **on ground.**

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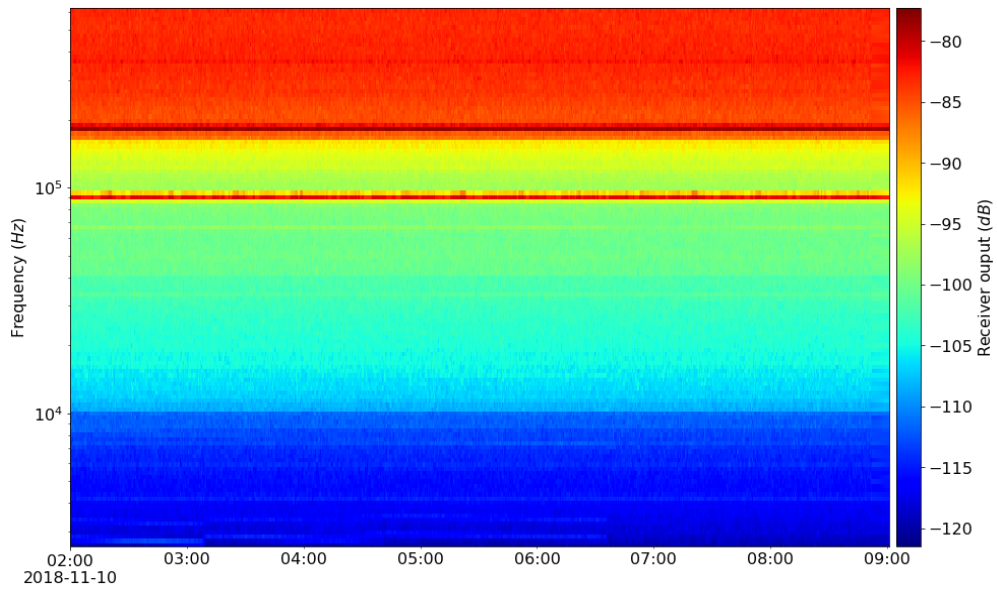


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872 **Figure 16: SORBET spectrogram of DB-SC (uncalibrated) data during NECP (the transfer**
873 **function of DBSC is not included).**

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878 **Table 1: Summary of LF-SC and DB-SC specifications.**

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Features	LF-SC	DB-SC
Sensors	194 grams (2 sensors) 14.4 × 17 × 116 mm	65 grams 17 mm (diameter) × 111 mm
Preamplifiers (in total)	324.7 grams, 100 × 90 × 48.2 mm	
Power (in total)	+/-12V, 384 mW	
Performance	0.1 Hz – 20 kHz	0.1 Hz – 20 kHz (LF) 10 kHz – 640 kHz (HF)
Sensitivity at 10 Hz pT/Hz ^{1/2}	3	2 (LF)
Sensitivity at 1 kHz fT/Hz ^{1/2}	40	50 (LF)
Sensitivity at 10 kHz fT/Hz ^{1/2}	40	50 (HF)
Sensitivity at 100 kHz fT/Hz ^{1/2}		10 (HF)

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