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Alfvén : Magnetosphere - Ionosphere Connection Explorers

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56 Abstract

57 The aurorae are dynamic, luminous displays that grace the night skies of Earth's high latitude
58 regions. The solar wind emanating from the Sun is their ultimate energy source, but the chain of
59 plasma physical processes leading to auroral displays is complex. The special conditions at the
60 interface between the solar wind-driven magnetosphere and the ionospheric environment at the top
61 of Earth's atmosphere play a central role. In this Auroral Acceleration Region (AAR) persistent
62 electric fields directed along the magnetic field accelerate magnetospheric electrons to the high
63 energies needed to excite luminosity when they hit the atmosphere. The "ideal
64 magnetohydrodynamics" description of space plasmas which is useful in much of the
65 magnetosphere cannot be used to understand the AAR.

66
67 The AAR has been studied by a small number of single spacecraft missions which revealed an
68 environment rich in wave-particle interactions, plasma turbulence, and nonlinear acceleration
69 processes, acting on a variety of spatio-temporal scales. The pioneering 4-spacecraft Cluster
70 magnetospheric research mission is now fortuitously visiting the AAR, but its particle instruments
71 are too slow to allow resolve many of the key plasma physics phenomena.

72
73 The Alfvén concept is designed specifically to take the next step in studying the aurora, by making
74 the crucial high-time resolution, multi-scale measurements in the AAR, needed to address the key
75 science questions of auroral plasma physics. The new knowledge that the mission will produce
76 will find application in studies of the Sun, the processes that accelerate the solar wind and that
77 produce aurora on other planets.

78 1 Introduction

79 The Alfvén mission concept proposes a new strategy for investigating universal plasma physical
80 processes that govern what Nobel laureate Hannes Alfvén named "The Plasma Universe". Such
81 processes encompass the acceleration of charged particles connected to the generation of
82 electromagnetic radiation, the development of strong plasma turbulence associated with the
83 maintenance of parallel electric fields along magnetic field lines in a collisionless plasma, and
84 complex ion heating phenomena leading to planetary ion outflow. The most accessible regions of
85 space for the study of these processes are the auroral regions of the Earth's magnetosphere.

86
87 The auroral regions are a key region of our solar system: they constitute the interface that connects
88 the distant solar wind-driven collisionless magnetosphere to the much denser ionospheric
89 environment at the top of Earth's atmosphere. A significant fraction of the energy fed in by the
90 solar wind to the magnetosphere is dissipated in this interface, often explosively during magnetic
91 substorms. In this transition region, the plasma organizes itself on small spatial and fast temporal
92 scales. The Auroral Acceleration Region (AAR) has been previously studied by a small number of
93 single spacecraft: S3-3 (1976), DE-1 (1981), Viking (1986), Freja (1992), Polar (1995) and FAST
94 (1996). High-time resolution FAST instruments revealed a plasma physics environment rich in
95 wave-particle interactions, plasma turbulence, and nonlinear acceleration processes, which implied
96 a variety of spatio-temporal scales. ESA's pioneering multi-spacecraft Cluster mission is now
97 exploring the AAR, revealing dramatic variability of large-scale auroral phenomena. Cluster can't
98 be used to relate these to phenomena observed by FAST as its particle instruments are too slow.

99
100 Key science questions related to the efficiency of acceleration processes and to their ability to
101 generate the complex features of auroral displays remain unanswered. In particular, high-time
102 resolution observations have suggested that acceleration by Alfvén waves would be responsible for
103 the generation of the sub-km scale auroral arcs. Single spacecraft measurements cannot evaluate
104 the energy exchanged over a large volume of space between waves and particles. They cannot
105 assess the efficiency of this mechanism, nor can they tell us where and when it is effective and
106 how it relates to the evolution of the magnetosphere - ionosphere connection. From high-time
107 resolution particle data, it has been proposed that localized parallel electric fields would explain
108 the larger scale arcs that can be observed by onboard imagers and that are associated with large
109 scale current structures that connect the magnetosphere to the ionosphere. Single spacecraft
110 measurements cannot follow the formation and evolution of these transient structures or the
111 complex transport phenomena associated with the strong plasma turbulence that develop along
112 magnetic field lines around these structures. Fundamental questions about auroral kilometric

113 radiation, its propagation and its fine structure, and about highly variable and diverse ionospheric
114 ion outflows, remain unanswered by earlier missions.

115

116 The Alfvén mission will be the first mission to combine high-time resolution and multi-scale
117 measurements in the AAR. It will fly through the heart of the AAR between a few 1,000 and
118 8,000 km altitude with two manoeuvrable spacecraft. Each spacecraft will carry the same high-
119 time resolution instrumentation. This is essential to allow appropriate inter-spacecraft correlations
120 and to solve the key science questions of auroral plasma physics. Thanks to the high-resolution
121 auroral imager present on both spacecraft, this mission will offer a truly outstanding opportunity to
122 unveil the mysteries of auroral displays. These unique capabilities together with a strong
123 coordination with the existing network of ground based observatories provide the opportunity to
124 improve our understanding of the magnetosphere - ionosphere connection. At the same time, the
125 Alfvén mission will allow Europe to achieve a real breakthrough in the physics of hot collisionless
126 plasmas. The near-Earth space plasma constitutes the most readily accessible cosmic plasma
127 system available for extensive and detailed *in situ* observations of these physical phenomena.
128 Dedicating this mission to Hannes Alfvén, we anticipate that it will not only tell us how our Solar
129 System works but it will also provide a unified Cosmic Vision of our Plasma Universe.

130 **2 Scientific Objectives and Requirements**

131 **2.1 Particle acceleration by Alfvén waves and the generation of small-scale** 132 **auroral arcs**

133 Auroral particle acceleration is a key topic in magnetospheric physics. Today there is a general
134 consensus that both quasi-static and wave electric fields contribute to field-aligned electron
135 acceleration in the collisionless auroral plasma. However, we have yet to establish whether these
136 acceleration mechanisms can provide sufficient energy and flux to stimulate discrete arcs over a
137 wide range of spatio-temporal scales, and the association between each acceleration process and
138 specific patterns of magnetosphere-ionosphere coupling is unclear.

139

140 Shear Alfvén waves are low-frequency waves that can support such accelerating parallel electric
141 fields when their perpendicular scale lengths are small enough. Single-point observations have
142 associated short-scale shear Alfvén waves– also called Dispersive Alfvén Waves (DAW)– with
143 accelerated electrons [1.1]. However, there are few studies which demonstrate that electrons might
144 gain energy at the expense of the waves during a single event due to the non-local nature of the
145 process that develops over large distances along the magnetic field. Measurements of particle and
146 wave energy at more than one location along the magnetic field are needed to fully characterize
147 the acceleration by Alfvén waves in the auroral regions. For example, Dombeck et al. [1.2] had to
148 rely upon a fortuitous conjunction between the Polar and FAST satellites, in order to correctly
149 diagnose that the acceleration mechanism was related to DAW. Given typical number density
150 profiles, acceleration can occur over distances of hundreds or even thousands of kilometers along
151 the magnetic field. Consequently, systematic observations of particle and wave energy by two
152 magnetically conjugate spacecraft are needed to fully characterize the acceleration by Alfvén
153 waves in the auroral regions.

154 *2.1.1 How efficient is Alfvénic acceleration in producing small-scale arcs?*

155 Numerical simulations indicate that Alfvénic electron acceleration can happen below 4,000 km
156 where inertial effects dominate [e.g. 1.3], and at higher altitudes where electron pressure effects
157 dominate [e.g. 1.4]. Depending on where and over which range of altitudes the Alfvénic
158 acceleration takes place, this process will produce different electron energies and fluxes and
159 auroral arcs of different widths and brightness [1.5]. Since the location of the acceleration is where
160 the waves develop sufficiently short perpendicular scales, interferometry [e.g. 1.6] can be used to
161 identify the perpendicular scales of the waves from electric and magnetic field measurements. This
162 will show whether short perpendicular scales develop as the wave propagates along the field, or
163 whether they have already developed at higher altitudes.

164

165 The Alfvén mission will supply this information by providing magnetic field conjunctions between
166 two spacecraft in a large range of altitudes, from ~1,000 km to 8,000 km and at different latitudes
167 and magnetic local times. The typical inter-spacecraft separation distance along the magnetic field
168 should be of the order of 100 km to several 100's km. Observations of plasma characteristics

169 including high-time resolution 2D electron pitch-angle measurements on a few 10's ms time scale
170 at multiple locations will be needed to identify short bursts of accelerated electrons. The ability to
171 distinguish between DAW and small-scale magnetic field-aligned currents is also very important
172 in the topside ionosphere [1.17]. Electromagnetic field data are necessary to diagnose the
173 properties of DAW, to perform Poynting flux measurements, and to assess the efficiency of the
174 Alfvénic acceleration process. By combining these data with ground-based optical data from
175 facilities in Scandinavia and in North America, we will be able to finally understand whether
176 Alfvén waves can feed sufficient energy into the electrons to create the small-scale (sub-km) arcs.

177 *2.1.2 How do Alfvén waves dissipate in auroral density inhomogeneities?*

178 Large scale density cavities (from ~10 km to a few 100's km across the magnetic field) are
179 observed above the auroral oval. It has been suggested that Alfvén wave fronts propagating onto
180 the edge of these cavities might distort which would lead to the formation of small perpendicular
181 scales [1.7]. Numerical simulations have shown that the energy budget of the process delivers net
182 electron acceleration and dissipation of the wave energy [1.8]. It is estimated that an Alfvén wave
183 could be dissipated in a few seconds. Some aspects of this scenario have been tested using FAST
184 observations in the topside ionosphere [1.9]. However, single spacecraft data cannot be used to
185 analyse the full energy budget of this process. Also, the efficiency of this mechanism is highly
186 dependent on the cavity configuration about which little is known from single spacecraft crossings.
187

188 The Alfvén mission will establish the role of auroral density inhomogeneities in generating
189 accelerated electrons. During the parallel phase of the mission, it will be possible to quantify the
190 Alfvén wave energy that is dissipated in density inhomogeneities. Typical inter-spacecraft
191 distances ranging from ~100 km to several 100's km will be needed. During the transverse phase
192 of the mission, when the two spacecraft will cross the edges of auroral cavities at different times,
193 we will develop a better knowledge of the temporal evolution of the density gradients. The
194 efficiency of the process heavily depends on the cavity lifetime which will be established by
195 systematic crossings at different altitudes, from ~1,000 km up to at least one Earth radius, and with
196 different delays between the spacecraft, from a few to several tens of seconds.
197

198 It will also be possible to identify cavity reformation processes: small scale secondary cavities may
199 be excavated during DAW propagation and they might lead to subsequent dissipation and electron
200 acceleration. Can the auroral system evolve from Alfvénic acceleration processes seen at the onset
201 of a substorm (see next paragraph) to a quasi-static situation with particle acceleration through
202 electrostatic structures such as strong double layers? If small-scale secondary cavities generated by
203 dissipating DAW are a precursor of larger scale auroral cavities, then the Alfvén spacecraft will be
204 able to observe this transition during the transverse phase of the mission.

205 *2.1.3 Do Alfvén waves accelerate electrons during substorm expansion phase onset?*

206 It is well known that stored energy transferred from the solar wind into near-Earth space is
207 explosively released during substorm expansion phase onset, powering aurora and generating
208 energetic particle populations [1.10]. The physics and the location of the region initiating the onset
209 of the substorm expansion have remained controversial for decades [e.g., 1.11]. It is also well
210 known that in the ionosphere, the first indication of a substorm onset is a sudden brightening of
211 one of the quiet arcs lying near the midnight sector of the oval (or a sudden formation of an arc).
212 However, the source of accelerated electrons that are responsible for this auroral brightening is not
213 clear, ~50 years following its discovery.
214

215 It has been suggested that broadband accelerated electron signatures are associated with Alfvén
216 wave activity following substorm onset [e.g. 1.12]. Furthermore, Newell et al. [1.13] presented
217 strong evidence that the electron energy flux from these broadband spectra increases significantly
218 at substorm expansion phase onset. Rae et al. [1.14] demonstrate that ground-based observations
219 of ULF wave amplitudes increase at the same time and in the same location as the first optical
220 signatures of substorm expansion phase onset in the ionosphere. Interestingly, the onset and
221 increase of ULF wave activity in the magnetosphere also occurs in close coincidence with the
222 onset of ground magnetic activity [e.g., 1.15], providing a tantalising glimpse of the link between
223 these ground-based perturbations and their possible magnetospheric counterparts. Taken together,
224 these results suggest that ULF wave-activity, broadband aurora and substorm expansion phase
225 onset may be intimately linked on short time scales, perhaps by the acceleration of electrons via
226 shear Alfvén waves [e.g. 1.4].

227 The sudden formation of a parallel electric field is essential to complete substorm onset. This
228 acceleration exhibits a two-step evolution as shown by auroral kilometric radiation observations
229 [1.16]: the activation of low altitude acceleration (4-5000 km) which corresponds to the initial
230 auroral brightening, and subsequent abrupt breakout of high altitude acceleration (above 6000 km)
231 which corresponds to auroral breakup (see Figure 2.1). During the parallel phase of the mission,
232 measurements along the same field lines at two different altitudes will show how electrons gain
233 the energy required to power the aurora at substorm onset times. The *in situ* measurements must be
234 made in regions of space conjugate to ground-based measurements of magnetic field and auroral
235 imaging in order to put the measurements in the context of the global substorm evolution.

236 **2.2 Parallel acceleration in magnetic field-aligned current structures**

237 Among the complex current systems which connect the magnetosphere to the ionosphere, the
238 auroral zone includes a region of quasi-stationary magnetic field-aligned currents where ion beams
239 drift away from the ionosphere along magnetic field lines while energetic electrons travelling
240 earthward "shower" the upper atmosphere. The associated inverted-V arcs are typically large scale
241 and stable structures compared to those described in Section 2.1. At 3,000-4,000 km altitude,
242 FAST satellite data have shown that a strong Double Layer (DL) localized within ten Debye
243 lengths $\sim 1-10$ km marks the transition from the topside ionosphere to a so-called auroral cavity
244 where the plasma is an order of magnitude more tenuous (see Fig. 2.2). Strong DLs associated
245 with an electric field of opposite polarity have also been shown to exist in the downward current
246 region where electrons of ionospheric origin are accelerated upwards.

247 *2.2.1 How do large amplitude strongly localized parallel electric fields form and evolve?*

248 Stationary models of DL and FAST data suggest that DLs propagate along magnetic field lines at
249 the ion-acoustic speed, which is of the order of 10 to 50 km/s in auroral regions. The amplitude of
250 the potential step along the field-lines is inferred from 3D electric field data. However these single
251 point measurements cannot explain how double layers form and evolve and they cannot tell us
252 whether the lifetime of these structures can account for the quasi-stationary nature of auroral forms
253 that are believed to be associated with them. Numerical simulations suggest that DLs form in 1D
254 current-driven plasmas in the presence of density fluctuations [2.2]. However, they might be
255 destabilized by their interaction with nonlinear ion structures emerging from the interaction of the
256 accelerated ion beam with thermal plasma after $\sim 500 \omega_{pi}^{-1}$, which corresponds to ~ 1 s in the auroral
257 regions [2.3]. This non-stationarity would mean that parallel acceleration by a single strong DL
258 cannot account for the quasi-stationary nature of inverted-V auroral arcs.

259
260 During the parallel phase of the mission, we will be able to detect DLs at two different altitudes, to
261 observe their time evolution, and to check for the stationarity of individual DLs. The time delay
262 for observing the structure by the two spacecraft should vary from a fraction of its expected
263 lifetime (~ 1 s) to a few times this number. Separation distances of 10 to 100 km are required to
264 answer these questions. An auroral imager with < 10 s time resolution is needed to follow the
265 evolution of the 10-50 km scale arcs associated with quasi-stationary field-aligned currents.

266 *2.2.2 What is the vertical structure of Auroral Accelerating Regions (AAR)?*

267 Large scale models of the vertical structure of AAR [2.4] show that the magnetic mirror effect and
268 the anomalous resistivity due to wave turbulence triggered by field aligned current might
269 contribute to maintain small amplitude quasi-stationary potential drops along auroral field-lines.
270 However numerical simulations taking into account the interaction between magnetospheric and
271 ionospheric plasmas show how strong DLs can play a key role [2.1]. Most of the electric potential
272 drop along the field-lines was found to be concentrated in two layers. While the low-altitude
273 transition layer of this model would correspond to the strong DL observed by FAST, the auroral
274 cavity would be bounded at higher altitude by a second transition layer, with a large potential drop
275 (several kV). Can we observe this high-altitude ion transition layer? Or is there a more complex
276 pattern of multiple transition/double layers that would simultaneously exist? Are these stationary
277 structures? If not, is there some kind of fast reformation mechanism of the structures that would
278 maintain a constant time-averaged accelerating potential along the auroral field-lines?

279
280 Measurements at two altitudes will quantitatively constrain the large scale models of AAR by
281 providing a clue on the distribution of particle distributions and electric fields. In the case of
282 unstable layers, it will be possible to identify reformation mechanisms. We will be able to test the

283 current–voltage relationship [2.5] that plays a key role in these models. Inter-spacecraft separation
284 distances from 50 to 500 km are required to answer these science questions. The main required
285 measurements are dc electric field, high-time resolution electron pitch-angle, and 3D ion
286 distributions together with auroral imager data in order to follow the evolution of the 10-50 km
287 scale arcs that are believed to be associated with quasi-stationary magnetic field-aligned currents.

288 *2.2.3 What are the properties of ion hole turbulence in the upward current region?*

289 In the upward current region, above the low-altitude DL, accelerated ionospheric ions drift at
290 different speeds due to their mass differences, whereby multi-stream plasma instabilities can
291 develop in the auroral cavity. The FAST satellite has indeed measured ion cyclotron waves and
292 nonlinear waves dubbed ion solitary waves [2.6]. The latter have propagation speeds in the
293 hundreds of km/s, typically the order of the ion beams, and are characterized by a bipolar electric
294 signal along the magnetic field with duration of 10 ms. They are usually referred to as ion holes.

295
296 Theory and simulations have shown that ion holes can form in the cavity 50 km above its bottom.
297 They result from the spatial growth of electrostatic waves destabilized by the two-stream
298 instability between the beams of H^+ and O^+ [2.7]. They propagate with a speed on the order of 200
299 km/s which is bracketed by that of the slow O^+ beam and the faster H^+ beam. From FAST
300 measurements it was concluded that the ion holes observed had a speed larger than the H^+ beam.
301 However only the electric field intensity and the time the structure takes to transit by the satellite
302 was directly measured. Its amplitude was indirectly estimated by evaluating the response of the
303 electron spectrum. From this estimate, the size and finally the speed of the structure was obtained.
304 Dual satellite measurements will provide a direct measure of the speed of ion holes by estimating
305 the delay of the electric field signature between the spacecraft. Spacecraft distances from 10 to 100
306 km are needed, corresponding to time delays <1 s over which ion holes are expected to be stable.

307
308 It is also known that O^+ ions have a larger pitch-angle than H^+ ions in these regions. This is either
309 due to the non-adiabatic motion of O^+ ions that cross the low-altitude DL or by the selective
310 perpendicular heating of low charge/mass ratio ions by ion-cyclotron turbulence. During the
311 parallel phase, we will be able to discriminate between the two models, since one mechanism
312 occurs at the transition layer itself while the other occurs 50-100 km above. A spacecraft
313 separation distance less than 200 km is needed in order to simultaneously monitor the transition
314 layer and the region where ion holes and ion cyclotron turbulence develop. To address this topic, it
315 is necessary to measure dc electric field and ULF/ELF waves and 3D ion distribution with mass
316 discrimination capabilities.

317 *2.2.4 What are the properties of electron hole turbulence in the downward current* 318 *region?*

319 In the downward current region (Fig. 2.3), strong DLs are associated with a strong plasma
320 turbulence composed of fast moving, large amplitude, Debye scale length, 3D electric field
321 structures that have been interpreted as electron phase space holes [2.8]. They are generated by
322 electron beam plasma interactions downstream of the accelerating DL. Their velocity has been
323 estimated by interpreting their magnetic signature as due to the Lorentz transformation in the
324 spacecraft reference frame of a purely electrostatic structure. However in weakly magnetized
325 plasmas, recent observations by THEMIS and CLUSTER spacecraft have shown that electron
326 holes can have a proper electromagnetic signature. Alfvén will investigate the nature (electrostatic
327 vs. electromagnetic) of electron holes and their velocity in the strongly magnetized auroral zones.
328 Dual spacecraft measurements will give a direct estimate of their velocity. It will then be possible
329 to derive their spatial size and amplitude, and to check the consistency of 3D electron hole models.

330
331 3D numerical simulations have observed the decay of 1D electron holes and the simultaneous
332 emission of lower-hybrid waves while stability analysis of 3D electron holes suggests that a
333 bounce resonance between trapped electrons and electrostatic whistler waves (from lower-hybrid
334 up to plasma frequency) might take place [2.9], which would reduce electron hole lifetimes. Since
335 electron holes have been frequently observed in association with bursts of Very Low Frequency
336 waves [2.10], electron holes might eventually dissipate by emitting these waves (VLF saucers).
337 During both parallel and transverse phases of the mission, the spacecraft will cross the source
338 region of VLF saucers and at the same time they will observe the development of electron holes
339 which will allow us to understand how this strong plasma turbulence dissipates.

340 **2.3 The Auroral Kilometric Radiation**

341 The very first satellites that carried radio receivers made the surprising discovery that Earth is an
342 intense radio source implying that energy also escapes from the auroral zone. This Auroral
343 Kilometric Radiation (AKR) extends from 50 kHz to 700 kHz. It is generated between 2,000 and
344 12,000 km altitude with a peak power at $\sim 5,000$ km. AKR, so named because at 300 kHz it has a 1
345 km wavelength in free space, is usually not detected on the ground because of shielding by the
346 ionosphere. The total AKR peak power levels can be as high as 10^9 W during strong substorms,
347 corresponding to several percent of the total substorm energy. Viking and FAST satellite
348 observations have shown that the emissions occur slightly below the local gyrofrequency in
349 regions of highly diluted plasma that contain earthward accelerated hot electrons (see Figure 2.4).
350 A Cyclotron Maser Instability (CMI) [3.2] occurs when electrons gyrating around the magnetic
351 field resonate with the background of EM waves. In the dilute auroral cavity, even weakly
352 relativistic non-Maxwellian electrons may invert the absorption coefficient of EM waves in the
353 plasma which radiates in concert like a maser and emits intense coherent radiation. CMI is most
354 efficient when the distribution of electron perpendicular velocities presents a positive gradient over
355 a significant fraction of the resonance curve [3.3]. FAST satellite data showed that parallel electric
356 fields in cooperation with the magnetic mirror force lift the electron distribution into an excited
357 level by generating a ring or horseshoe distribution with a strong perpendicular gradient. The
358 radiation is emitted primarily in the Right hand polarized eXtraordinary(RX)-mode at the local
359 relativistic electron gyrofrequency into a strictly perpendicular direction with respect to the
360 magnetic field [3.4].

361 *2.3.1 How does the radiation escape?*

362 It is not understood however how the radiation escapes from the local density cavities where it is
363 generated. The AKR source region lies within a density cavity bounded by a region containing a
364 much denser thermal population (see Fig. 2.5). The perpendicular (to the magnetic field)
365 dimension of the AKR source is typically ~ 100 km. The source region emissions are generated in
366 the RX-mode, above the RX cutoff frequency which is an increasing function of the density and
367 the magnetic field strength. Thus the density gradient at the edges of the cavity will reflect the
368 radio waves, and in addition, earthward propagating emissions will also reflect due to the
369 increasing magnetic field strength nearer the Earth.

370
371 There are several possible windows of escape: for example, mode conversion to the R-mode which
372 has a nearly parallel propagation with a small optical depth along the magnetic field, or
373 alternatively, partial or total mode conversion at the dense plasma walls boundary into either the Z
374 mode or the L-O mode. These modes have different polarization patterns. The CMI mechanism
375 itself is expected to produce strongly elliptically polarized waves that shall consequently be
376 observed at least within AKR sources. From outside of the cavities, AKR has been observed to
377 display quasi-purely circular polarization [3.5] with a possible small parallel component [3.6]. The
378 Alfvén spacecraft will measure the complete AKR polarization state. With two spacecraft at 10 to
379 100 km separation distance and at different oblique angles relative to the static magnetic field, it
380 will be possible to understand how mode conversion works. Poynting flux estimates will be
381 essential to quantify the efficiency of the conversion mechanisms, to understand polarization
382 transfers along the ray path and which information is carried by the radio waves reaching free
383 space.

384 *2.3.2 What generates the AKR fine structure?*

385 The second unresolved problem is the enormous fine structuring of the radiation as illustrated in
386 Figure 2.6. The spectral resolution of the AKR emission strongly suggests that a large part of the
387 emission is made up of narrowband (down to less than 100 Hz) drifting structures. Often, the
388 central frequency of the individual emissions varies in a systematic manner, sweeping either
389 upward or downward across the spectrum. As AKR emissions take place near the electron
390 cyclotron frequency, earthward (anti-earthward) drifts in space are reflected by upward
391 (downward) drifts in frequency-time diagrams. Assuming a dipole magnetic field geometry, a
392 bandwidth $\Delta f \sim 100$ Hz corresponds to ~ 1 km for the radial size Δz of the elementary radiation
393 structures. The speeds of the elementary radiators can be derived from the measurement of their
394 instantaneous df/dt ; according to their bandwidth they are quite variable and range from the ion
395 acoustic velocity to the electron thermal velocity.

396

397 The simplest assumption is to identify the emission sources with real, drifting small-scale (1 km
398 corresponding to several Debye lengths) physical objects. It has been speculated that electron [3.7]
399 or ion [3.8] phase-space holes associated with double layers as well as double layers themselves
400 [3.9] might play a key role in generating different AKR fine structures: the parallel electric field
401 they carry would locally modify the electron distribution function and would enhance the
402 radiation. However, simultaneous measurements by two satellites crossing the AKR source region
403 at two different altitudes are required to validate this scenario. Two satellites located a small
404 distance apart along the same magnetic field lines (or close by) crossing an AKR source region at
405 the same time will measure the AKR frequency structures together with the characteristics (scales
406 and velocities) of any turbulent nonlinear structures moving along the magnetic field lines,
407 enabling a test of the scenario.

408
409 The possibility of a relationship between Alfvén waves and the generation of such AKR fine
410 structure must be investigated as well. An Alfvén wave process is believed to play a role in the
411 origin of some of the brightest short-burst Jovian radio emissions [3.10]. Fine structure in AKR
412 emissions has also been observed at Earth in Alfvénic auroral acceleration regions between 2,500
413 and 3,600 km [3.11]. With the two Alfvén spacecraft, it will be possible to investigate the
414 generation of AKR short bursts by Alfvén wave accelerated electrons, with one spacecraft crossing
415 the source region while the other is observing the escaping radiation.

416 **2.3.3 Towards astrophysical applications**

417 The AKR source regions are identical to the auroral particle acceleration regions, implying that
418 AKR is the only auroral phenomenon that provides remote information about the vertical structure
419 and dynamics of the acceleration region. For instance, AKR has been used to characterize the two
420 step-evolution of auroral acceleration at substorm onset [1.15]. Most of the information we have
421 about acceleration/heating processes comes from the radiation emitted by astrophysical objects
422 over a wide range of wavelengths. The AKR from the Earth can be taken as the paradigm for other
423 manifestations of intense radio emissions.

424
425 The application of the CMI concept has been very efficient for explaining radiation from Jupiter
426 and from other solar system magnetized planets [3.12]. The first crossings of the SKR source
427 region at Saturn [3.13] display very close similarities with the terrestrial AKR counterpart, with
428 some evidence of shell-like electron distributions. Another interesting similarity is that Saturn's
429 SKR also exhibits a dual source character which might be linked to magnetotail reconnection and
430 plasmoid/substorm evolution [3.14]. These results demonstrate that parallel acceleration and CMI
431 generation processes do not only occur at Earth. Advances in studies of these phenomena at Earth
432 will be applied in order to remotely probe the auroral regions of other magnetized planets.

433
434 More generally, the mechanisms may be active at magnetized planets, magnetic stars, flare stars,
435 pulsars, and active galactic nuclei or blazars [3.15]. Speculations about radiation emitted from
436 sufficiently strongly magnetized extra-solar planets have been published [3.16]. Scaling laws have
437 been derived from solar system planetary radio emissions that relate the emitted radio power to the
438 power dissipated in the various corresponding flow-obstacle interactions. Extrapolating these
439 scaling laws to the case of exoplanets, it has been suggested that hot Jupiters may produce very
440 intense radio emissions due to either magnetospheric interaction with a strong stellar wind or to
441 unipolar interaction between the planet and a magnetic star. Radiation of this kind, because it
442 would be much stronger than any other radio emission, would allow not only allow detection of
443 "radio-loud" extra-solar planets but also the inference of their magnetic field strengths and plasma
444 properties. Because of its unique measurement capabilities, Alfvén will bring an improved
445 understanding of AKR, which is needed if AKR is to become a reliable tool to probe astrophysical
446 objects and, for example, to detect and/or characterize extra-solar planets.

447 **2.4 Ionospheric ion outflows**

448 The magnetosphere of the Earth has two plasma sources, the solar wind / magnetosheath at the
449 outer boundary and the ionosphere at the inner boundary. The auroral ionosphere is a particularly
450 important source of plasma during magnetic storms, when heavy ions of ionospheric origin can
451 become dominant in large parts of the magnetosphere [see e.g. 4.1]. The final fate of ionospheric
452 ions is dependent both on the magnetic connection between the source region and the
453 magnetosphere and on the typical energy of escaping ions. The large-scale impact of ion outflow
454 also strongly depends on its mass flux. Cusp outflow is most likely to escape from the

455 magnetosphere. Polar cap and polar cap boundary layer outflow is more likely to contribute to
456 auroral dynamics and the development of auroral storms. None of these different source regions
457 are uniform in space and time in the way they provide ionospheric material to the distant
458 magnetosphere. Studies have shown a one-to-one relationship between poleward moving auroral
459 forms (PMAFs) and ion upflow events in the auroral cusp, which indicates that the ion outflow
460 phenomenon is driven by pulsed reconnection [4.2]. Ionospheric ion outflow can also induce the
461 formation of low conductance regions which may affect the electrodynamics of the ionosphere-
462 magnetosphere interaction. Finally ion outflow, in particular from the cusp and polar cap, is
463 important from a planetology point of view, as this outflow may be lost from the atmosphere and
464 thus affect atmospheric evolution on the long term [4.3].

465 *2.4.1 What is the spatio-temporal variability of ion extraction mechanisms?*

466 The amount of ion outflow is critically dependent on the source altitude of the outflowing plasma.
467 The richest source is typically the ionospheric F region, located at an altitude of typically 300-500
468 km. It consists mostly of O⁺. Processes that can extract plasma from the ionospheric F region or
469 below are most effective in locally removing O⁺ ions. They can lead to very low ionospheric
470 densities which, if the E region is also affected, can lead to conductance structures which will
471 affect the auroral electrodynamics. The initial upflow of plasma from the F region can be studied
472 by radars like the EISCAT facility but so far they only provided altitude profiles from one point
473 [4.4].

474
475 Two perpendicularly separated spacecraft will for the first time allow us to measure the spatial
476 scales over which the extraction mechanisms operate, and separate this from the time scales for
477 intermittent extraction. The initial upflow results from Joule heating in the ionosphere and from
478 enhanced ambipolar diffusion caused by elevated electron temperatures which in turn are caused
479 by (mainly soft) electron precipitation [4.5]. If there is no further energisation of the ions at higher
480 altitude the ions will fall down into the ionosphere again. Even a little heating, well below what is
481 needed to reach escape velocity, may stop the ions from returning to the ionosphere due to the
482 effect of the mirror force. Ions may thus stay in an intermediate region until they are heated
483 enough to overcome gravity [4.6].

484
485 Two spacecraft separated in the perpendicular direction will allow us to study the spatial scales
486 and persistence of such waves, as well as the drift of gravitationally bounded ions which are kept
487 from returning to the ionosphere through the mirror force of the magnetic field. Systematic
488 measurements by spacecraft aligned along the field-line will show if the waves are typically
489 present over large distances along the field-line or if they only exist in narrow regions. Ions may
490 also be trapped by downward directed field-aligned electric fields, not just gravity, or be heated in
491 the parallel direction. Perpendicularly separated spacecraft will show how these conics evolve with
492 time, whereas altitude separated spacecraft can show how they evolve along the field-line.

493 *2.4.2 How efficient are the various ion energisation mechanisms?*

494 Throughout the outflow path the ions may be subject to heating and acceleration. In the main
495 auroral oval direct acceleration by parallel electric fields is expected to be an important driver in
496 the nightside and in the afternoon sector. However, wave particle interaction leading to transverse
497 heating is expected to be the most important mechanism at low altitude and over extended altitude
498 intervals in the dayside cusp/cleft and in the polar cap boundary layer in the nightside. Among the
499 many energisation mechanisms depicted on Figure 4.1, Alfvén wave turbulence, that often takes
500 the form of broadband ELF waves, has been studied by e.g. Chaston et al. [4.7]. It is a good
501 candidate for the formation of regions of depleted plasma. However, it is also well-known that the
502 presence of background field-aligned currents (which are themselves related to the dynamics of the
503 aurora) affect the presence of ion cyclotron waves which can directly heat ions through a resonant
504 process. FAST measurements show that the electron beam drives electrostatic ion cyclotron waves
505 both in upgoing ion and upgoing electron beams [4.8]. Heating may also occur in association with
506 density cavities, in particular lower hybrid cavities, low density regions which are filled with
507 intense lower hybrid waves [4.9]. Another acceleration mechanism which is important at least for
508 cusp and polar cap ion outflow is the centrifugal acceleration mechanism that has been studied
509 with the Cluster spacecraft at high altitude [4.10]. Finally oblique field-aligned electric fields, as
510 already described in Section 2, might also be important in regions of strong field-aligned currents.
511

512 A two spacecraft mission with varying perpendicular separation will allow us to study for the first
513 time the structuring of both waves and particles at different spatial scales, thus allowing us to
514 characterize and understand the turbulence that is related to ion heating. We will be able to
515 systematically probe the scale size and lifetime of associated cavities and of field-aligned current
516 regions. We will observe how associated electric fields and ion distribution functions evolve in
517 and around the cavity / field-aligned currents. Altitude separated spacecraft will allow us to study
518 the propagation of waves and turbulence along the field lines. These measurements will constrain
519 the numerical models that integrate along magnetic field-lines the cumulative effect of specific
520 energisation mechanisms and we will be able to assess their relative efficiency. Mass resolved
521 measurements will be most important to distinguish between these different acceleration
522 mechanisms since many of them are mass dependent. Such processes occur at all planets where
523 ion outflow has been detected, but only at Earth is it likely that we will ever have the multi-point
524 measurements appropriate to study the mechanisms leading to ion heating and outflow.

525 **3 Mission Profile**

526 **3.1 Introduction**

527 The minimum requirement in order to meet the science goals discussed here is for a well
528 instrumented dual spacecraft mission, in which the spacecraft separation is varied along and across
529 the magnetic field for selected length scales, covering the range of altitudes at which auroral
530 particle acceleration occurs. During the preparation of the concept proposed to ESA, an alternative
531 three spacecraft mission concept was also developed. The three spacecraft mission offered
532 advantages such as the possibility of simultaneous measurements of perpendicular and parallel
533 scales, and less severe reduction in science return in the event of instrument or even spacecraft
534 failure. The three spacecraft mission was also more expensive and while it was not expected to
535 exceed the mission cost cap, the team choose to propose the two spacecraft variant which is
536 discussed in detail in this paper.

537 **3.2 Orbit Requirements**

538 *3.2.1 Operational Orbits*

539 The scientific aims of the mission require that dual-spacecraft operations are performed over the
540 range of altitudes and magnetic latitudes where the auroral acceleration region is located.
541 Coverage of all magnetic local times is required, although a subset is of prime interest for studies
542 of the substorm onset region in the pre-midnight MLT sector, and of the cusps on the dayside
543 centred on noon MLT. For science planning purposes, we referred to a statistical study of the
544 probability of observing accelerated auroral electrons with energy flux $> 0.25 \text{ erg cm}^{-2} \text{ s}^{-1}$ for all
545 IMF conditions [MP.1] and in particular an improved quality figure based on that study [MP.2].
546 The region of maximum probability is within the ranges; ILAT 65° - 75° , MLT 20-22 hrs; and a
547 wider region of high probability is within the ranges; ILAT 70° - 80° , MLT 12-18 hrs; ILAT 65° -
548 75° , MLT 18-24 hrs.

549
550 We present one possible orbit strategy that we have developed, with some assistance from CNES
551 and Astrium. We note that more detailed follow-on studies might well result in a better optimised
552 approach.

- 553
- 554 - Initial orbit: 500 km circular polar orbit. This is used for commissioning and as a parking
555 orbit before transition to the main operational orbits, improving launch date flexibility.
- 556 - Reference Orbit 1 (RO1): 500 km x 4000 km elliptical polar orbit, (similar, but not
557 identical to the orbit of the FAST spacecraft).
- 558 - Reference Orbit 2 (RO2): 500 km x 8000 km elliptical polar orbit.
- 559 - De-orbit phase: reduce perigee to 250 km, atmospheric drag gradually causes deorbit.
- 560

561 In Table 3.1 we summarise strawman parameters for the main science mission. For simplicity we
562 set the spacecraft transition to RO1 to occur on the autumn equinox, at which time the orbit plane
563 is required to lie in the noon-midnight meridian. The plane of the RO1 polar orbit is fixed in
564 inertial space and will rotate about the Earth once per year (similar to Cluster or Double Star TC-
565 2). The line of apsides of the RO1 orbit will rotate around within its orbit plane once in 192 days.

566 We wish to achieve magnetic conjunctions with the region of highest probability of observing
567 accelerated auroral electrons while at apogee in northern hemisphere winter months, to favour co-
568 operation with ground based optical observatories. We determined that to achieve this, the
569 argument of perigee of the initial RO1 orbit should be 192° on 22 September. Similarly, the
570 transition to RO2 which should ensure that conjunctions continue to occur over that region as the
571 mission progresses, and we chose a transition date of 10 November 2022 at which point the
572 argument of perigee (in both RO1 and RO2) is 290° . In Table 3.1 we summarise the mission orbits
573 and timeline, and indicate an arbitrarily selected date to end the RO2 phase after two years.
574

575 Figure 3.1 shows that there are 4 intervals with conjunctions in the 18-24 MLT sector in the
576 northern hemisphere in the 2 years of the RO1 orbit. There are 2 more while in the RO2 orbit
577 together with 2 intervals in the 12-18 MLT sector. There are also a similar number of southern
578 hemisphere intervals which are equally useful for *in situ* measurements, but which will be less well
579 supported by ground-based facilities. Since the period of rotation of the line of apsides is not an
580 integer fraction of 1 year in either RO1 or RO2, the coverage pattern of the auroral oval changes as
581 the mission proceeds, as indicated in Figure 3.1 (this is an area where further optimisation may be
582 possible). The distribution in time and in ILAT/MLT of useful magnetic conjunctions while the
583 spacecraft are in the AAR altitude range will be higher than shown in Figure 3.1 since the plots
584 concentrate on the apogee intervals and ignore time when the spacecraft are elsewhere on their
585 orbits but are also within useful ILAT/MLT regions.
586

587 Figure 3.2 (upper panel) shows our estimates of the accumulated time spent with the spacecraft
588 magnetic footprint in the auroral zone; the red line refers to the 12-18-24 MLT semi-oval, showing
589 values of 1-2 hours per day in RO1 and more in RO2. The black line refers to all MLTs, i.e. the
590 complete auroral oval, and shows roughly double the accumulated time.
591

592 Significant additional scientific opportunities will arise by combining space measurements made
593 by Alfvén with simultaneous conjugate observations of the aurora and of the detailed nature of the
594 conjugate ionosphere made by ground observatories, particularly in Northern Europe and North
595 America. Nordic infrastructure today [MP.3] includes EISCAT, Super-DARN, MIRACLE
596 (Magnetometers, Ionospheric radars, Allsky Cameras Large Experiment), ALIS (Auroral Large
597 Imaging System) and ASK (Auroral Structure and Kinetics). Furthermore, funding has been
598 awarded for the planning of future capabilities in this region, specifically EISCAT_3D and SIOS
599 (Svalbard Integrated Arctic Earth Observing System). As an indication of how often such
600 observations will be possible, Figure 3.2 (lower panel) shows the accumulated time spent with the
601 spacecraft magnetic footprint above the Scandinavian MIRACLE network, which ranges between
602 5-25 minutes in RO1 and ranges up to 50 minutes in RO2. These values were determined with 1
603 minute resolution orbit data and magnetic mapping using the current IGRF magnetic field model,
604 accounting for the Earth's rotation, spin axis orientation and dipole tilt. There will be additional
605 useful conjunctions with the network of ground-based facilities in North America but we do not
606 assess those here.
607

608 The red and blue filled rectangles highlight the times at which the spacecraft conjunctions are in
609 the regions of high probability of observing accelerated auroral electrons. It is clear from Figure
610 3.2 that these coincide with the longer duration intervals of magnetic conjunctions with the auroral
611 regions and intersections with the MIRACLE network, demonstrating that our mission design is
612 reasonably effective.
613

614 The main science goals of the mission will be addressed with both spacecraft in each of the
615 Reference Orbits, by varying the inter-spacecraft separation in two phases; a radial (parallel)
616 separation phase (phase A) and a transverse separation phase (phase B). In our strawman mission
617 outline, there are 2 years in each of RO1 and RO2; further study is required to determine the most
618 appropriate division of the time between phase A and phase B operations, but the simplest
619 approach is to share it equally.

620 3.2.2 Phase A: Parallel Spacecraft Separations

621 A possible method of achieving suitable parallel separations is to modify the eccentricity of the
622 orbit of one spacecraft without changing the semi-major axis. Differential drift of the argument of
623 perigee produces a tilt between the lines of apsides of the orbits of the two spacecraft. The
624 consequent radial spacecraft separation is indicated in Figure 3.3. The process can be reversed on
625 the same spacecraft, or executed on the second (which leads to more similar fuel usage on the two

626 spacecraft) to stop the differential drift. It is more efficient to achieve the eccentricity change by
627 decreasing perigee and raising apogee than vice versa. It is necessary to ensure that the two
628 spacecraft are properly synchronised so that they arrive in the auroral region together, separated
629 primarily along the magnetic field (\sim radially) without transverse separation. This can be achieved
630 with proper planning as demonstrated by Cluster. The differential drift is relatively expensive in
631 Δv and fuel. For example, the drift to 4° tilt would take ~ 3 months if using a Δv of 200 m/s. More
632 fuel can achieve a given change more rapidly

633 **3.2.3 Phase B: Transverse Spacecraft Separations**

634 During this phase the spacecraft will be separated along the orbit track. A possible method is to
635 temporarily alter the semi-major axis of one spacecraft, while preserving the eccentricity of its
636 orbit. Small impulses at perigee and apogee can be used to achieve this, firstly to modify the orbit
637 and then to return it to the original parameters. For small fuel costs (fractions of a kg,
638 corresponding to $\Delta v < 1$ m/s), the spacecraft separation can be varied by up to 100 km scales
639 within 1 day. Changes can be executed more quickly for larger fuel costs. In practice, a separation
640 scale will be selected for a set of orbits before the scale is changed to another value and the process
641 is repeated. The along track time delay for a 10 km separation at apogee is ~ 2 s, rising linearly to
642 20 s for a 100 km gap. We note that operations at comparable small separations have already been
643 achieved during the ESA-NASA Cluster mission and will soon be demonstrated in the NASA
644 Magnetospheric Multi-scale Mission.

645 **3.3 Launcher and Spacecraft Manoeuvring Requirements**

646 **3.3.1 Launch to Initial Orbit**

647 The proposed launcher is Vega. The two Alfvén spacecraft can be launched from the Guiana
648 Space Centre into an initial 90° inclination polar orbit of altitude 500km. The Vega User Manual,
649 (March 2006 version) indicates that the launch vehicle can deliver 1623 kg to this orbit. We show
650 below that the proposed spacecraft mass including fuel and 25% margin is of order 1500 kg, and
651 thus is well within the launch vehicle performance capability. Further orbital changes can be
652 performed with spacecraft onboard thrusters, following the example of Cluster.

653 **3.3.2 Transfers to Reference Orbits**

654 The feasibility of using Vega to launch two Alfvén spacecraft, each with adequate fuel to perform
655 the mission phases outlined above, is shown in Table 3.2. The calculation is conservative as it
656 assumes that all fuel needed for the Phase A and B operations (“Small Scale Manoeuvres”) is
657 retained until the end of the mission, while in practice it would be used progressively during the
658 mission. The specific impulse figures cover a range of values which includes the 280-290 s
659 specific impulse of Cluster 10 N thrusters in pulsed or continuous mode and the 300 s recommend
660 by Astrium for such thrusters. The 320 s case would be for a 400 N main engine as on Cluster, but
661 not baselined for Alfvén, included for comparison. Astrium recommended that we consider 20%
662 of the total fuel mass to be a good estimate of propulsion system mass (tanks, thrusters, associated
663 structure). It is clear that after including a 20% system level margin, two spacecraft can be
664 delivered to the planned 500 x 500 km altitude initial orbit by Vega. If for some reason Vega
665 performance is in fact lower than expected at this stage of its development, our mission profile
666 could be correspondingly adapted by lowering the apogees of the orbits, most likely without a
667 major impact on the science.

668 **3.3.3 Extended mission concepts**

669 The nominal mission lifetime described here is 4 years. Significantly longer operations may be
670 possible based on the experience of FAST in an orbit similar to RO1 (> 10 years). Extended
671 operations in any of the scientifically preferred configurations would be valuable, in order to
672 improve statistics and coverage of the altitude range at all MLT.

673

674 An additional mission phase which could follow the RO2 phase would involve extending the
675 differential drift of the line of apsides to 180° , allowing simultaneous imaging of the northern and
676 southern hemispheres, and collection of related *in situ* data. This would provide the first

677 opportunity to systematically study the effects of the different ionospheric illumination expected in
678 the two hemispheres.

679 **3.4 Ground Segment Requirements**

680 As noted above, the line of apsides will rotate completely around the Earth, in about 6.5 months
681 for RO1 and 11 months for RO2. In order to provide good ground station visibility while lingering
682 near apogee, ground stations in both the northern and southern hemispheres are required. Figure
683 3.4 shows that the daily average minimum contact time for the ESA Kiruna ground station is as
684 low as 1 hour, which can be improved to a minimum time of 4 hours if support is also provided by
685 the Perth ground station. It is clear that there are some individual orbits where contact time with a
686 single ground station is very low, so the spacecraft would ideally have the capability to store data
687 from more than one orbit between opportunities to transmit the data to a ground station.
688 Alternatively, as proposed here it may be more cost effective to use a second ground station in the
689 other hemisphere, to ensure that there are always contact intervals of a sufficiently long duration to
690 transmit data from at least one orbit.

691
692 A preliminary study has demonstrated the feasibility of meeting the planned data return
693 requirements using these ESA ground stations (for further discussion see Section 5).

694 **4 Model Payload**

695 **4.1 Overview of all proposed payload elements**

696 Each spacecraft has an identical payload, consisting of a suite of Fields and Particles sensors
697 together with a UV auroral imager. The payload is summarised in Table 4.1 and discussed in
698 Section 4.3 below. For the purposes of the study, three Data Processing Units were described (for
699 the Fields, Particles and Imager) since the resources required could be conveniently estimated
700 based on previous work. A more detailed study may show that a combined unit could deliver the
701 necessary functionality within a smaller resource allocation than for the three separate DPUs.
702

703 The mass of wire/stacer booms is included in E3D. The mass of the main rigid booms (4 m) is
704 included in MAG and HFML respectively. The mass of the MNLP booms is included under
705 MLNP. These mass and power totals may be compared with the corresponding values for the
706 highly integrated payload of the smaller FAST spacecraft, which were 65 kg and 39 W.

707 **4.2 Proposed payload accommodation**

708 The suggested accommodation for the “fields” equipment is shown in Figure 4.2. There are a pair
709 of 40 m tip-to-tip electric field booms in the spin plane; a pair of 7 m tip-to-tip spin axis electric
710 field stacer booms; two 4 m rigid booms to support the magnetometers, search coils, and loop
711 systems. In addition, a pair of 0.7 m booms support the Langmuir needle probes; these are tilted
712 out of the spin plane by $\sim 30^\circ$.

713
714 Figure 4.3 illustrates how the plasma instruments are mounted on a main experiment platform,
715 looking out through the curved surface of the cylindrical spacecraft. The field of view of the
716 plasma instruments are indicated in Figure 4.3. Plasma and Imager Instruments should be aligned
717 with the local spacecraft radius to within 15 arcseconds. Their field of view should be clear, with
718 margin, and should not be affected by glint. The two EESA sensors should be diametrically
719 opposite one another, so that their combined field of view is 360° in each case. Similarly for IESA.

720 **4.3 Proposed Instrument Complement**

721 **4.3.1 Overview**

722 The payload of the Alfvén mission and its accommodation on the spacecraft platform is fully
723 adapted to the study of the AAR at high-time resolution. The Electron and Ion ElectroStatic
724 Analyzer (EESA and IESA) provide a 2D pitch-angle distribution within 40 and 100 ms,
725 respectively (compared to 2 to 4 s on Cluster). The 3D electric fields will be measured by E3D
726 instead of 2D electric fields on Cluster, which is essential in order to study parallel electric fields.

727 Key magnetic field measurements are fully redundant with 2 MAG sensors, also allowing
728 correction of any residual magnetic interference from the spacecraft. MAG and MADAM
729 observations have some overlap and will be cross-calibrated. HFML provides a 3D measure of
730 high-frequency magnetic waves (there was no measurement of this type on Cluster), which is most
731 important for AKR studies. CDC will for the first time partially solve the basic spatio-temporal
732 ambiguity between small-scale (typically between 10 m and 5 km) current structures and
733 dispersive Alfvén waves. The High Frequency Receiver (HFR) will continuously provide the
734 complete spectral matrix of electromagnetic waves which will be a first at high frequency in the
735 AAR and a key measurement to understand how AKR escapes from the AAR and to quantify this
736 process.

737
738 All instruments are at Technology Readiness Level (TRL) 5 or higher at the time of writing, with
739 the exception of IESA which is in development and expected to reach TRL 5 by spring 2012. Most
740 instruments have spaceflight heritage, often from multiple missions, and use technologies that are
741 well established in Europe.

742
743 All instruments will have a standby mode (reduced power but ready to quickly begin science
744 measurements) and one or more (but few) science operations modes. Options for internal
745 calibration modes or engineering modes are anticipated. Some instruments may need specific
746 commanding when the system shifts from slow survey to fast survey to burst mode.

747
748 All instruments will undergo appropriate ground calibration. In-flight inter-calibration of
749 instruments will be carried out using routinely acquired datasets.

750 *4.3.2 3D Electric Field:*

751 The E3D electric field experiment provides rapid measurements of 3D electric field to an accuracy
752 of 1 mV/m on the two spin plane components and 10 mV/m on the spin axis component, up to a
753 limit of 1 V/m. It also provides an estimate of spacecraft potential up to 50 V. The technique
754 involves measuring the probe-spacecraft potential differences on pairs of probes on opposite sides
755 of the spacecraft. In addition to measuring slowly varying local electric fields, electric components
756 of electrostatic and electromagnetic waves of frequencies up to a few MHz can be measured and
757 are received and processed by other experiments (the Low and High frequency Receivers). The 20
758 m long spin plane wire booms are deployed from units mounted on the main experiment platform.
759 The spin axis stacer booms are shorter (3.5 m long) in order to minimise disturbance to spacecraft
760 attitude stability. Sensors and preamplifiers are placed at the ends of the booms.

761 *4.3.3 Magnetic Field: MAG*

762 The MAG magnetic field experiment provides rapid measurements of the 3D magnetic field vector
763 in the bandwidth DC to 64 Hz in fields as strong as 65,000 nT. Instrument accuracy is of order 0.1
764 nT, but the practical resolution of the measurements is sized in proportion to the measured field
765 intensity due to the digitalization of the signal. With 16 bit data words, it would be 2nT. The
766 planned rate of science data is 16 vectors/second. The technique is the widely used fluxgate
767 method. The instrument consists of two tri-axial fluxgate magnetic field sensors, mounted at
768 different distances along one of the rigid booms to allow identification and correction for any
769 unexpected magnetic interference from the spacecraft. The magnetometer alignment must be
770 stable and known to an accuracy better than 0.1°, translating to a requirement for a rigid boom and
771 spacecraft attitude knowledge known to better than 0.1°.

772 *4.3.4 Magnetic field: MADAM*

773 Disturbances to the magnetic field in the frequency range 0.1 Hz to 25 kHz will be measured by
774 the MADAM instrument, which also measures the magnetic field from quasi-DC to a few Hz with
775 an auxiliary sensor. The main sensor is a magnetic field search coil which consists of tri-axial loop
776 sensors, and the auxiliary sensor is a miniature magnetoresistive sensor which is incorporated into
777 the search coil mount. The magnetic field strength resolution is +/-10 nT in the flat part of the
778 search-coil transfer function from 100 Hz to 10 kHz and 20 dB/decade higher outside the flat part,
779 and +/-0.1nT for the auxiliary sensor. The instrument sensitivity can be expressed in terms of
780 equivalent input magnetic noise levels as low as : <20 pT/√Hz at 1 Hz, 2 pT/√Hz at 10 Hz, 0.2
781 pT/√Hz at 100 Hz, 0.025 pT/√Hz at 1 kHz. The instrument is designed to ensure that the
782 maximum magnetic field at the spin frequency does not saturate the search coil output. The sensor

783 must be mounted on a rigid boom, at least 1 m from the spacecraft. Adequate separation from
784 other boom payloads should also be provided. Supporting analog electronics may be mounted with
785 the sensors on the boom, or at the foot of the boom.

786 4.3.5 *Magnetic field: HFML*

787 Disturbances to the magnetic field in the frequency range 20 kHz to 2 MHz will be measured by
788 the High Frequency Magnetic Loop instrument [P1], which thus complements the search coils.
789 HFML uses 3 loops of diameter 20 cm each, and provides measurements of all three magnetic
790 components, similar to the search coil. The instrument will measure Auroral Kilometric Radiation
791 emissions, which have peak intensity in the 100's kHz range. Instrument bandwidth is 3 dB and
792 sensitivity is 0.3×10^{-6} nT/ $\sqrt{\text{Hz}}$ at 1 MHz for a 20 cm diameter coil. The sensor and associated
793 analog electronics must be mounted on a rigid boom at least 1m from the spacecraft to minimise
794 spacecraft electromagnetic interference.

795 4.3.6 *Electric Current Density: CDC*

796 The varying current density in the ELF frequency range can be directly measured by a Current
797 Density Coil sensor [P2]. The sensor consists of a 15cm diameter toroidal coil with primary and
798 secondary windings, and the measured quantity is AC current flowing through the loop. The
799 technique is based on Ampère's Law. Taking account of spacecraft motion, this will reveal
800 changes in current density (in a specific direction) as the spacecraft crosses field aligned current
801 layers, even double layers, associated with auroral arcs. By comparing measurements from the 2
802 spacecraft during the transverse phase, it will be possible to identify the proper motion of small-
803 scale current structures. It will enable the distinction between small-scale current structures and
804 Alfvén waves. The bandwidth is 3 dB (1 Hz – 450 Hz) and sensitivity is 0.3×10^{-6} A m⁻²/ $\sqrt{\text{Hz}}$ at
805 10 Hz and 1.0×10^{-6} A m⁻²/ $\sqrt{\text{Hz}}$ at 1 Hz. The sensor and associated analog electronics must be
806 mounted on a rigid boom at least 2 m from the spacecraft to minimise spacecraft electromagnetic
807 interference.

808 4.3.7 *Electromagnetic wave signal processing unit and sounder: AWI*

809 The main function of the Alfvén Wave Instrument is to digitize analog signals from the 3 fields
810 and waves instruments HFML, E3D, and MADAM, to calculate Fourier spectra of the signals and
811 to prepare data products that can be passed to the Fields DPU for downlink or on-board storage. It
812 also contains an active sounder that excites plasma resonances in order to probe the absolute value
813 of the electron plasma density. Internally, AWI is composed of three hardware modules that would
814 share a common electronic box:

815
816 HFR: The High Frequency Receiver will provide unique information about electromagnetic
817 radiation in space plasmas by performing, for the first time, a complete goniopolarimetric study of
818 Auroral Kilometric Radiation and other emissions like VLF saucers. The HFR performs duty
819 cycled snapshot digitization of one of the electric and magnetic signals from the HFML or E3D
820 instruments. It calculates the power spectra of 5 of the electric and magnetic signals in the
821 frequency range between 8 kHz and 2 MHz together with their cross-spectra from which
822 information about k-vector, polarization, and Poynting flux can be derived.

823
824 EDEN: The electron density will be measured at high altitudes using the “relaxation sounder”,
825 Electron DENsity, which is capable of measuring densities in the range 0.1-100 cm⁻³. Thus EDEN
826 complements MNLP which measures denser plasmas, although EDEN operates at a lower rate
827 than MNLP. The instrument consists of a transmitter which operates in partnership with the High
828 Frequency Receiver. In “passive mode” the transmitter is inactive and the receiver picks up natural
829 emissions in its frequency range. Operation in active mode produces plasma resonances that are
830 detected by the receiver, from which plasma density can be determined. Transmitter activity lasts a
831 few seconds at a time, and is employed perhaps only once every 1 minute, as it interferes with
832 measurements from the other Fields instruments. Knowledge of the absolute electron number
833 density is valuable for calibrating the particle instruments, cross-calibrating the magnetometer
834 measurement (via the electron gyro-frequency), as well as for scientific studies. The method has
835 been used in the AAR by Cluster. The transmitter frequency range will be increased for Alfvén.

836
837 LFR: The Low Frequency Receiver provides complete information on Alfvén waves and strong
838 double layers as well as on the wave turbulence associated with AKR and ion energisation

839 mechanisms. The LFR digitizes 6 electric probe potentials “6xV” and 3 electric field components
840 “3xE” from E3D as well as 3 magnetic field oscillations from MADAM in the frequency range
841 from DC up to 25 kHz. Using a downsampling scheme, it can provide continuous or duty cycled
842 waveforms of these 12 quantities at various sampling rates (256 Hz, 25 kHz). It calculates their
843 power and cross-spectra. Time resolution of the spectra can vary with mode.

844 4.3.8 *Electron Electrostatic Analyser: EESA*

845 The pitch angle distribution of auroral region electrons is measured at the fast rate of 40 ms, for
846 the energy range 4 eV to 32 keV using the Electron Electro-Static Analyser instrument which
847 consists of two sensor units, each with a top hat electrostatic analyser and an electrostatic aperture
848 deflection system at the entrance to the top hat. The sensors must be mounted on opposite sides of
849 the spacecraft. The field of view of the combined instrument lies in the spin plane, but can be
850 deflected through a few 10s of degrees as needed to ensure that it includes the magnetic field, so
851 that continuous full pitch angle coverage is assured. There will be a total of 32 angular sectors
852 giving pitch angle resolution of 11.25°. The geometric factor is based on the Cluster PEACE
853 HEEA instrument, and at $1.73 \times 10^{-2} \text{ cm}^2 \cdot \text{str.eV/eV}$ is a factor 3.4 larger than for the FAST EESA
854 (a factor 0.28 of the FAST SESA spectrograph) so that the instrument will be well optimised for
855 auroral electron fluxes, but able to collect distributions more quickly. The time to collect a full
856 energy-pitch angle distribution with good statistics will be 40 ms (perhaps 20 ms), i.e. at least
857 twice as quick as FAST. In order to sweep faster the accumulation step will be 1 millisecond and
858 there will be 40 log-spaced energy steps spaced at about 1.5x the analyser FWHM $\Delta E/E$, 16%.

859 4.3.9 *Ion Electrostatic Analyser: IESA*

860 The full 3D velocity distribution of ions is measured at the fast rate of 100 ms, for the energy
861 range a few eV to 30 keV using two sensors comprising the Ion Electro-Static Analyser. The
862 sensors must be mounted on opposite sides of the spacecraft. The technique involves a system of
863 concentric toroidal plates with a wide effective aperture covering 2π sr solid angle coverage, that
864 guide ions to a 2D detector plane, where arrival directions are measured with $\sim 12^\circ \times 12^\circ$ angular
865 resolution. Energy selection is achieved using swept high voltages to provide 48 log-spaced energy
866 channels at an energy resolution of 16%. The geometric factor of the pair of sensors is 0.1
867 $\text{cm}^2 \cdot \text{str.eV/eV}$, an order of magnitude larger than for the IESA on the FAST mission, allowing a
868 time resolution of 100 ms with good counting statistics.

869 4.3.10 *Ion Composition Analyser: ICA*

870 The full 3D velocity distribution for several key ion species is measured at a rate of twice per spin,
871 for the energy range a few eV to 10 keV using a single sensor Ion Composition Analyser. The
872 instrument will distinguish protons and oxygen ions even for weak fluxes, and will be able to
873 resolve all major ion species (H^+ , He^+ , He^{2+} , O^+) in strong flux situations. Thus the sensor
874 complements IESA, trading speed for simultaneous information about different ion species and
875 finer energy resolution (10%). The instrument consists of a top hat entrance with electrostatic
876 analyser followed by a light weight time of flight (i.e. non-magnetic) mass discrimination system
877 which also has the advantage that the anti-coincidence system is relatively unsusceptible to false
878 counts from penetrating radiation. The instrument is mounted on the curved face of the spacecraft,
879 and its top hat field of view provides instantaneous $360^\circ \times 11.25^\circ$ coverage, which is swept
880 through 4π sr during half a spacecraft spin. Typically the instrument would use 8 ms accumulation
881 bins and a 32 step (sparse) energy sweep, collecting data from 16 anodes and 6 time-of-flight
882 windows. The angular resolution is thus 22.5° in azimuth and 15° in polar (controlled by spin rate
883 and energy sweep period). The geometric factor of the instrument is $8 \times 10^{-3} \text{ cm}^2 \cdot \text{str.eV/eV}$.

884 4.3.11 *Multi-Needle Langmuir Probes: MNL*

885 The electron density is measured at a rate of up to 10 kHz, over a density range of $\sim 10^2 \text{ cm}^{-3}$ to
886 $\sim 10^6 \text{ cm}^{-3}$, (corresponding to altitudes below ~ 3000 km) using a system of 3 needle probes on each
887 of 2 booms, comprising the Multi-Needle Langmuir Probes [P3]. The technique relies on the
888 principle that probe current squared (I_e^2) plotted versus probe potential (V_p) is a straight line, of
889 which the growth rate is proportional with the electron density squared. The quality of the electron
890 density measurements can be judged by checking the linearity of I_e^2 versus V_p . This method is
891 effective when the spacecraft potential is -1 to -2 V, which is expected in the relatively dense
892 ionospheric plasma below 3,000-4,000 km altitude, but ceases to be useful in more rarefied plasma

893 where the spacecraft potential is a few V positive (as may be confirmed using the E3D
894 instrument). The probes are operated at a constant potential and do not generate electromagnetic
895 noise that could affect other instruments. The probes will provide reliable data as long as they are
896 not in the spacecraft wake. The wake extends in the direction opposite to the spacecraft velocity
897 vector and its size varies with the local Debye length that increases with altitude (of order 1 m at
898 altitudes between 4,000 and 5,000 km). The proposed probe mounting of probes on two booms as
899 illustrated above is intended to ensure that at least one probe triple is always outside the wake.

900 **4.3.12 Wide-Field Auroral Imager: WFAI**

901 Auroral images at UV wavelengths will be collected from the band 140-180 nm which includes
902 the molecular N₂ Lyman-Birge-Hopfield (LBH) emissions, using the Wide Field Auroral Imager
903 [P4]. The images contain photometric information, allowing the measurement of auroral emission
904 intensity as a function of location and time. The wide instantaneous field of view (tens of degrees)
905 combined with the orbital motion of the platform, permits large swathes of the auroral emission
906 region to be observed during each spacecraft pass. The instrument sensitivity limits are between 60
907 Rayleigh and 20 kRayleigh. The angular resolution is ~ 15 arcminutes, hence the spatial resolution
908 is ~2 km from a 500 km altitude apogee; 18 km from 4,000 km, and ~35 km from 8,000 km.
909 Fields of view from each of the two planned operational orbits are illustrated in Fig 4.4.

910 The instrument is relatively small because it uses a radially-slumped micro-channel plate optical
911 system in conjunction with a slumped photon-counting MCP detector. The optics and detector are
912 separated by an interference filter deposited in a CaF₂ substrate, which simultaneously selected the
913 UV band of interest and prevents electrons reaching the detector. In particular, the filter rejects the
914 intense Lyman- α emission at 121.6 nm, permitting auroral emission to be imaged in both the dark
915 and sunlit ionospheres. The readout anode provides high spatial resolution at high count rates and
916 signal processing capability within the detector. Individual photons are detected and their arrival
917 time noted to nanosecond accuracy, easily meeting the requirement for millisecond accuracy in
918 order to allow reconstruction of an image from a spacecraft rotating with a 6 second spin period.
919 The instrument should be mounted with the boresight perpendicular to the rotation axis, passing
920 through the nadir once per rotation. The spacecraft accommodation should ensure no glint affects
921 the instrument. Spacecraft attitude knowledge accurate to a few arcmins is required, and onboard
922 timing should be accurate to 1 millisecond resolution.

923 **4.3.13 Data Processing Units**

924 The Fields data processing unit deals with data collection and control for E3D, MAG, MADAM,
925 HFML and CDC. It also hosts the LFR, HFR and EDEN equipment, and provides data processing,
926 compression, and packetisation functions. The design is dual redundant. The particles data
927 processing unit deals with data collection and control for EESA, IESA, ICA, and LMP. The
928 system functionality includes power conversion for attached sensors, local data storage, data
929 processing, compression, and packetisation functions. A dedicated DPU was envisaged to support
930 the WFAI sensor. This has quite high resource requirements; a study of a significantly less
931 resource intensive design is planned (a factor 4 lower in mass and power)

932 **4.4 On board data handling and Telemetry**

933 Table 4.2 shows the proposed telemetry rate for each instrument for each of the three data
934 collection modes; slow survey, fast survey and burst mode. A triggered 30 s HFR super high time
935 resolution E or B waveform snapshot requiring 300 Mbit is also planned for each orbit. The total
936 rates are comparable to those of the FAST mission, which used a similar strategy.

937
938 For example, using typical numbers from FAST of a 133 minute period orbit and a 40 minute
939 auroral region crossing, we could consider 93 minutes in Slow Survey followed by the auroral
940 region crossing of which 35 minutes was in Fast Survey and 5 minutes in Burst Mode. The
941 accumulated data volume would be 246 Mbyte.

942 **4.5 Requirements on the Spacecraft: Interfaces, pointing and alignment**

943 The spacecraft spin axis should align with the spacecraft symmetry axis to within 0.5° to 95%
944 confidence level (as Cluster). The spin axis should not nutate. The suggested spin period is 6 s
945 however this parameter is flexible and should be reassessed in a detailed study phase. A shorter
946 spin period would allow shorter intervals between imager observations of the Earth, but spin axis

947 control becomes more difficult due to the axial E3D booms. The spin axis direction and rotation
948 phase knowledge requirements of $\pm 0.25^\circ$ and $\pm 0.20^\circ$ are proposed based on Cluster.
949
950 The spacecraft attitude should be maintained close to the orbital plane, and to within 10° of the
951 typical local magnetic field direction in the auroral region (magnetic latitudes 65° - 75°) in order to
952 support auroral particle measurements. It is also important that the spacecraft attitude should be
953 controlled when the spin plane is near the Earth-Sun line to prevent the Sun entering the line of
954 sight of the outward facing particle and imager instruments, and to avoid the E3D probes entering
955 shadow. The spin axis should not lie with 80° - 100° of the spacecraft-Sun vector.
956
957 No instruments require radiators or active thermal control in normal operation.

958 **5 System Requirements & Key Issues**

959 The Alfvén spacecraft have identical design and construction, and identical payloads. In preparing
960 this proposal we are guided by experience with the NASA FAST spacecraft and the ESA Cluster
961 spacecraft. The technical implementation of the FAST mission is described in detail in several
962 papers in Space Science Reviews, Vol 98, Nos 1-2. The FAST spacecraft operated successfully in
963 a 350 km x 4175 km 83° inclination orbit, very similar to our 500 km x 4000 km Reference Orbit
964 1. Although its nominal lifetime was 1 year, its operational lifetime exceeded 10 years. Its science
965 and payload design drivers are the same as for Alfvén, with two exceptions. Firstly, the Alfvén
966 spacecraft will carry a wide field auroral imager. Secondly, the Alfvén spacecraft will carry
967 sufficient fuel to alter their orbits; to vary their separation relative to one another, to modify their
968 operational orbits and eventually to de-orbit themselves. The Cluster spacecraft flotilla have
969 demonstrated that extensive manoeuvring, of the type we propose for Alfvén, may be done with
970 small 10 N bipropellant thrusters. The Cluster spacecraft 400 N main engine was only used to get
971 from GTO to the initial operational orbit. All other manoeuvres were achieved with 10 N thrusters.

972 **5.1 Attitude and orbit control**

973 The preferred spacecraft attitude is with the spin axis perpendicular to the velocity vector, i.e.
974 parallel to the orbit plane normal. Ideally the spin plane is close to the local magnetic field plane at
975 auroral latitudes, as noted in Section 4.5. The FAST mission achieved this goal by tilting the
976 spacecraft spin axis relative to the orbit plane normal by $\sim 3^\circ$, towards alignment with the Earth's
977 axis, so that the magnetic field lay within $\sim 10^\circ$ of the spin plane. The arrangement is also
978 compatible with the Alfvén auroral imager field of view requirement. All electric field boom tips
979 should remain in sunlight. The other constraint on attitude is solar beta angle. FAST maintained
980 this at $90^\circ \pm 30^\circ$, in order to ensure that spacecraft power and thermal constraints were respected.
981 Depending on the design of the Alfvén spacecraft, a wider range of beta angle may be acceptable.
982 Further study is needed to investigate how this constraint may conflict with the optimum attitude
983 for scientific measurements, for example when the spacecraft orbit plane is perpendicular to the
984 spacecraft-Sun line. FAST used magneto-torquers at low altitudes to achieve control of the spin
985 axis. Attitude was sensed with a combination of a sun sensor, horizon crossing indicators and the 3
986 axis magnetometer.

987 **5.2 On-board data handling and telemetry**

988 The FAST model of data collection involved "slow survey" data collected for a large fraction of
989 the orbit during intervals of low electron flux, "fast survey" when electron fluxes exceed a
990 threshold, and "burst" data during short intervals when specific triggers indicating passage through
991 regions of particular interest (and even a "high speed burst for very short intervals"). FAST used a
992 1 Gbit solid state recorder which is too small to contain 40 minutes of data collected in fast survey
993 mode let alone burst mode, and smaller than could be downlinked in a typical contact period.
994 Consequently the FAST team invested significant effort in onboard triggering to try to capture
995 intervals of particular interest and managed the filling state of the recorder orbit by orbit.
996

997 Our planned telemetry levels are similar to those of FAST, and by using a similar approach we
998 could return them in the same way (the data volume mentioned in Section 4.4 could be
999 downlinked in a 20-30 minute contact period at the maximum rate used by FAST). We propose a
1000 simpler approach, taking advantage of the larger capacity mass memory now available (8 Gbit was
1001 used on DEMETER, 32 Gbit may be realistic now) which allows us to return more complete
1002 coverage in fast survey mode with an opportunity for a fixed fraction of each auroral crossing to

1003 be collected in burst mode. In order to return the larger data volume, either a longer contact period
1004 would be used (FAST communications duration were apparently power limited, but we plan a
1005 spacecraft with higher power) or else the following orbit would be used to complete the downlink
1006 before new science data collection occurred.

1007 **5.3 Mission operations concept (ground segment)**

1008 The mission will be operated by ESOC, with communications being handled by the ESA ground
1009 station network. The commanding and data recovery are envisaged as following the model of
1010 Cluster or Double Star, in terms of spacecraft and payload control via time tagged commands, pre-
1011 planned a few weeks ahead of execution, and regular scheduled data downlinks, ideally with
1012 onboard data storage margin to allow a second try if a downlink is interrupted or not achieved for
1013 some reason. Payload commanding will be prepared via a SOC in collaboration with PI teams. As
1014 discussed in 3.4 above, the precession of the line of apsides means that ground stations will be
1015 needed in both hemispheres. Figure 3.4 shows ground station access times determined using STK
1016 software for the two main reference orbits, using ESA ground stations at Kiruna and Perth. This
1017 confirms that the longest contact times in the 500 x 4,000 km orbit are of order 3,000 s (similar to
1018 FAST) and shows how ground stations in opposite hemispheres complement one another to ensure
1019 continuous availability of contact times of 2-3,000 seconds (30-50 mins), adequate to downlink an
1020 orbit of data with some margin. The longer period 500 km x 8,000 km orbit offers contact times of
1021 up to 5,500 s. ESOC will collect the data from the ground stations and to make it available to PI
1022 teams via the SOC or MDC.

1023 **5.4 Estimated overall resources (mass and power)**

1024 We propose that the Alfvén spacecraft have a diameter of 2 m and a height of ~1m. These
1025 dimensions are larger than FAST due to the need to accommodate fuel tanks and thrusters to
1026 facilitate orbit manoeuvres and due to the need for a larger solar panel area to support the higher
1027 planned payload average power. We also make the assumption that less highly integrated
1028 spacecraft sub-systems may be more cost-effective for an ESA mission and we seek to provide a
1029 greater degree of redundancy than was possible within the FAST design constraints. A stack
1030 consisting of a pair of 2m diameter spacecraft, each ~1m high, is consistent with the Vega launch
1031 shroud constraint.

1032
1033 The proposed spacecraft mass breakdown is shown in Table 5.1. The estimate is based on the
1034 FAST spacecraft where appropriate. Changes include (i) doubling the mass of subsystems which
1035 grow in proportion to the doubled diameter, (ii) doubling the mass of the batteries, (iii) adding
1036 10% to other sub-systems using the recommended Design Maturity Margin principle, (iv) adding
1037 mass for fuel tanks and thrusters following the principle that their mass is 20% of the required fuel
1038 mass (as advised by Astrium engineers). In addition there is an ESA system margin of 20%.

1039
1040 We show in Table 5.1 that the planned beginning of life (BOL) solar array power is sufficient to
1041 meet the demand (including ESA system margin) after 3 years, assuming a power decline at the
1042 same rate as FAST. A slightly longer mission such as the 4 year mission we describe in section 3
1043 would involve a further degradation of only a few W, and does not seem an unreasonable
1044 proposition at this early stage in the mission design work. Batteries are needed to support the
1045 spacecraft during eclipses of up to 45 minutes duration.

1046 **5.5 Specific environmental constraints (EMC., temperature, cleanliness)**

1047 In order to minimise spacecraft disturbances to the space plasma environment and to the
1048 measurements, the spacecraft magnetic field and electric fields should be kept to a low level. Good
1049 quality “magnetic cleanliness” can be achieved by making it a design requirement on the
1050 spacecraft and payload, and by an explicit activity testing and verifying performance. Similarly, an
1051 electrostatic cleanliness programme is required. The solar array and all other spacecraft surfaces
1052 should be part of a single uniformly conducting surface in order to avoid localised areas of
1053 differential surface charging with corresponding localised electric fields. An Indium Tin Oxide
1054 coating on solar array cover glass provides the required conductivity. Other spacecraft surfaces
1055 should have a covering of conducting MLI (multi-layer insulation) that is kept electrically
1056 connected to the spacecraft structure. An electromagnetic cleanliness programme should ensure
1057 that spacecraft sub-systems do not generate interference with measurements of high frequency
1058 electric and magnetic field disturbances due to plasma waves.

1059
1060 The “particles” and “imager” instruments use micro-channel plate detectors and high voltages, and
1061 require a vacuum for safe operation. During spacecraft assembly and test it is necessary to provide
1062 dry nitrogen purge for these instruments. During the initial days in orbit, time should be allowed
1063 for out-gassing before these instruments are commissioned.

1064
1065 Temperatures for inboard payload and spacecraft subsystems are expected to be kept within a
1066 typical range of perhaps 5° to 30° C, with a margin of order 10° C. Outboard sensors are designed
1067 for colder temperatures during normal operations and may need heaters to cope with eclipses.

1068 **5.6 Special requirements**

1069 We note that the radiation environment for this mission is relatively harsh. The Alfvén spacecraft
1070 design should take account of this. Using SPENVIS we estimate the annual dose in Reference
1071 Orbit 1 (500 km x 4,000 km, $i = 90^\circ$) as 84/48/11 krad behind the equivalent of 3/4/5mm
1072 aluminium. The annual dose reduces to ~ 52/24/11 krad in Reference Orbit 2 (500 km x 8,000 km,
1073 $i = 90^\circ$) for 3/4/5 mm aluminium equivalent. For comparison, we understand that the Solar Orbiter
1074 and Bepi-Colombo mission radiation doses are ~100 krad; our 4 year mission concept dose would
1075 be similar for shielding of order 4-5 mm Aluminium. The dose behind 4mm Aluminium is
1076 essentially the same dose tolerated by subsystems in the interior of FAST for 10 years, according
1077 to a SPENVIS analysis of the FAST orbit. The longevity of the FAST spacecraft demonstrates the
1078 success of the FAST design approach which could serve as a model for Alfvén.

1079 **6 Technology Development, Programmatics and** 1080 **Cost**

1081 **6.1 Technology Development requirements**

1082 No major spacecraft design challenges are foreseen, as all relevant technologies have already been
1083 demonstrated by mission such as FAST, THEMIS, Cluster and the soon-to-be launched MMS.
1084 Similarly, payload technology development requirements are rather minor. All the payload will be
1085 at TRL5 by 2012 and all apart from IESA and WFAI have extensive flight heritage.

1086 **6.2 Overall mission cost analysis**

1087 Although detailed mission cost estimates are difficult, especially at such a preliminary stage, we
1088 note that following ESA’s guidelines for an initial estimate, our mission concept cost falls well
1089 inside the ESA M3 mission cost cap.

1090 **6.3 Mission Schedule Drivers, Risks and Alternate Strategies**

1091 There are no mission design related schedule drivers. The launch date is relatively flexible and not
1092 tied to narrow launch windows as might be the case for example for a typical planetary mission.
1093 Due to the low technical risk associated with the payload and the spacecraft designs, the mission
1094 could be carried out on the timescale envisaged for the ESA M3 mission, leading to a launch as
1095 early as late 2020.

1096 **7 Communication and Outreach**

1097 The aurora borealis or “northern lights” have captivated onlookers since the earliest humans
1098 arrived in the polar regions. Cultures around the arctic circle have developed a range of myths and
1099 folklore in order to explain the appearance of these ghostly lights in the night sky and this keen
1100 interest in one of nature’s most spectacular natural phenomenon continues to the present day. The
1101 aurora regularly appears in popular culture through film, television and literature while an entire
1102 industry has developed to enable tourists to view the northern lights first-hand from cruise liners,
1103 pleasure flights and arctic holidays.

1104 **8 Conclusions**

1105 The Alfvén mission concept is designed to make a major step forward in understanding the plasma
1106 physics processes that ultimately generate the beautiful ever-changing aurora. These processes are
1107 not well understood and their study will produce insights with applicability across a wide range of
1108 astrophysical phenomena. A multi-spacecraft mission with sufficiently fast fields and particles
1109 instrumentation is essential to meet this goal.

1110
1111 The strong scientific return outlined in this paper can be achieved using a two spacecraft mission
1112 which could be implemented quickly, costs significantly less than the ESA Medium Class mission
1113 cost cap, does not rely on international partnerships and which does not involve technological
1114 risks that might later drive up costs or introduce programme delays.

1115
1116 In closing, we note that a three spacecraft mission, likely also affordable within the ESA M3 cost
1117 cap, was also studied but is not reported here. The concept offers greater insurance against the risk
1118 of instrument or spacecraft problems, and improved science return in some areas.

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| Orbit Phase | Perigee x apogee (km) | Orbit period | Line of apsides rotation period (days) | Mission phase start (d/m/y) | Phase duration (days) |
|---------------|-----------------------|--------------|--|-----------------------------|-----------------------|
| Initial Orbit | 500 x 500 | 1 h 34 m | n/a | flexible | flexible |
| Ref. Orbit 1 | 500 x 4,000 | 2 h 13 m | 192 | 22/09/20 | 780 |
| Ref. Orbit 2 | 500 x 8,000 | 3 h 02 m | 331 | 10/11/22 | 721 |
| De-orbiting | 250 x 8,000 | 2 h 58 m | tbc | 09/11/24 | tbc |

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1295 **Table 3.1** Summary of the strawman mission design parameters

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| Spacecraft Details | | | |
|--|--------|--------|--------|
| Engine Specific Impulse (s) | 270 | 300 | 320 |
| Dry Mass excluding propulsion system h/w (kg) | 285 | 285 | 285 |
| Dry Mass including propulsion system h/w (kg) | 343 | 340 | 339 |
| Fuel available for SSMs (kg) | 50 | 50 | 50 |
| Mass after LSMs, incl. SSMs fuel (kg) | 393 | 390 | 389 |
| Initial orbit | | | |
| Apogee altitude (km) | 500 | 500 | 500 |
| Inclination (deg) | 90 | 90 | 90 |
| Total Mass Vega can deliver to this orbit (kg) | 1623 | 1623 | 1623 |
| Large Scale Maneuvers (LSMs) | | | |
| Phase 1 Apogee Altitude (km) | 4000 | 4000 | 4000 |
| ΔV to Apogee (km/s) | 0.7374 | 0.7374 | 0.7374 |
| Phase 2 Apogee Altitude (km) | 8000 | 8000 | 8000 |
| ΔV to Apogee (km/s) | 0.5119 | 0.5119 | 0.5119 |
| De-orbiting Perigee Altitude (km) | 250 | 250 | 250 |
| ΔV to Perigee (km/s) | 0.0531 | 0.0531 | 0.0531 |
| Fuel and propulsion | | | |
| Total ΔV for LSMs (km/s) | 1.3024 | 1.3024 | 1.3024 |
| Fuel required for LSMs (kg) | 236.4 | 223.34 | 216.69 |
| Estimated propulsion system h/w [20% fuel] (kg) | 57.279 | 54.667 | 53.337 |
| Mass Budget | | | |
| Spacecraft Wet Mass at launch (kg) | 629.4 | 613.34 | 605.69 |
| Spacecraft Wet Mass (kg) + ESA system margin @ 20% | 755.28 | 736 | 726.82 |
| Two Spacecraft Wet Mass at launch (kg) | 1510.6 | 1472 | 1453.6 |
| Mass margin within Vega capability (kg) | 112.45 | 150.99 | 169.35 |

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Table 3.2 Demonstration that the spacecraft, payloads and fuel can be launched by Vega

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| Payload Element | Abbrev. | CBE | | TRL 2010 |
|--|----------|--------------|--------------|-------------|
| | | Mass/kg | Power/W | |
| Electric and magnetic fields; electromagnetic and electrostatic waves | | | | |
| Electric field: 3D | E3D | 7.40 | 1.83 | 8 |
| Magnetic field: 3D d.c. | MAG | 4.23 | 3.00 | 7 |
| Magnetic field: 3D a.c. (SC/MRM) | MADAM | 1.22 | 1.43 | 5 |
| Magnetic field: 3D HF loop | HFML | 4.55 | 0.64 | 6 |
| Current density (a.c.) loop/coil | CDC | 2.01 | 0.40 | 6 |
| Wave analysis (8kHz-2MHz) | AWI-HFR | 1.50 | 5.00 | 7 |
| Wave analysis (DC-16kHz) | AWI-LFR | 0.45 | 3.20 | 5 |
| Radio Sounder (electron density) | AWI-EDEN | 0.80 | 2.07 | 8 |
| Fields DPU | AWI-DPU | 2.80 | 6.79 | 6 |
| Plasma characteristics | | | | |
| Electron distributions: 2D (fast) | EESA | 6.90 | 5.40 | 5 |
| Ion distributions: 3D (fast) | IESA | 7.10 | 6.00 | 4 |
| Ion distributions: 3D (mass) | ICA | 1.90 | 6.43 | 7 |
| Multi needle Langmuir probes | MNLP | 4.28 | 3.40 | 6 |
| Particles DPU | PDPDU | 2.20 | 5.80 | 6 |
| Auroral Imaging | | | | |
| Wide Field Auroral Imager (UV) | WFAI | 3.56 | 10.51 | 5 |
| Imager DPU | IDPU | 1.80 | 6.15 | 5 |
| TOTALS | | 52.70 | 68.04 | |

Table 4.1 Summary of the proposed Alfvén payload (mass and power excluding ESA margins)

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| Payload Data Rates | Slow Survey kbit/s | Fast Survey kbit/s | Burst kbit/s |
|------------------------------|-----------------------|-----------------------|-----------------|
| MAG | 1.54 | 1.54 | 1.54 |
| LFR DC | 3.07 | 3.07 | 3.07 |
| LFR LF | | 28.67 | 49.15 |
| LFR MF | | | 3,932.16 |
| LFR MF Spectra | 4.27 | 102.40 | |
| HFR spectra | 3.20 | 6.40 | 6.40 |
| CDC | | 32.00 | 32.00 |
| EDEN | 0.20 | 0.20 | 0.20 |
| Fields/Waves Subtotal | 12.28 | 174.28 | 4,024.52 |
| EESA | 2.05 | 20.50 | 512.00 |
| IESA | 1.02 | 24.58 | 360.45 |
| ICA | 5.00 | 48.00 | 48.00 |
| MNLP | 0.16 | 1.60 | 16.00 |
| Particles Subtotal | 8.23 | 94.68 | 936.45 |
| WFAI | 2.70 | 27.00 | 135.00 |
| Imager Subtotal | 2.70 | 27.00 | 135.00 |
| TOTAL | 23.21 | 295.96 | 5,095.97 |
| FAST | 50.00 | 500.00 | 8,000.00 |

Table 4.2 Summary of payload data production rates for three rates of data collection

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| Spacecraft Subsystem | Mass /kg | Spacecraft Subsystem | Power /W |
|---------------------------------------|----------|-------------------------------------|---------------|
| Payload incl. booms | 62.28 | | |
| Mission Unique Electronics | 16.17 | Power demand | |
| Battery/Shunt | 25.00 | Payload (all operating) | 81.11 |
| Solar array | 70.80 | Spacecraft (excl Transmitter) | 50.00 |
| ACS | 10.67 | RF system | 28.00 |
| RF system | 5.72 | Subtotal | 159.11 |
| Thermal system | 3.30 | ESA system margin @20% | 31.82 |
| Harness | 18.20 | TOTAL required | 190.93 |
| Test connector panel | 0.44 | | |
| Structure | 53.00 | | |
| Balance weight | 10.60 | Power supply | |
| Launch adaptor | 4.00 | Solar array EOL | 187.2 |
| Miscellaneous | 4.40 | (ESA 20% margin on" BOL + 3 years") | |
| Subtotal | 284.58 | | |
| Tanks, thrusters, pipes (20% of fuel) | 58.00 | | |
| TOTAL | 342.58 | Solar array EOL | 234 |
| ESA system margin @20% | 68.52 | (3 years, 10% margin = FAST actual) | |
| GRAND TOTAL DRY MASS | 411.10 | | |
| Fuel | 290.00 | | |
| ESA system margin @20% on fuel | 58.00 | | |
| GRAND TOTAL WET MASS | 759.10 | Solar array BOL required | 260 |

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1424 **Table 5.1** Summary of spacecraft subsystem mass, and of power budget. Ongoing further work
1425 shows that some of these can be reduced, for example GaAs solar array technology would allow a
1426 significant mass reduction in the solar array.

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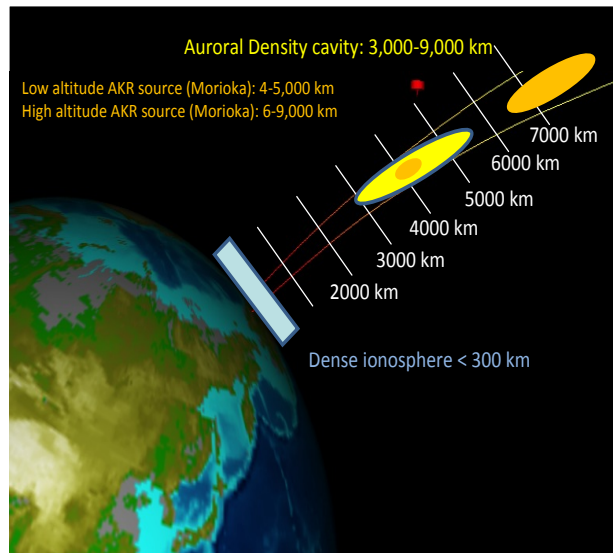
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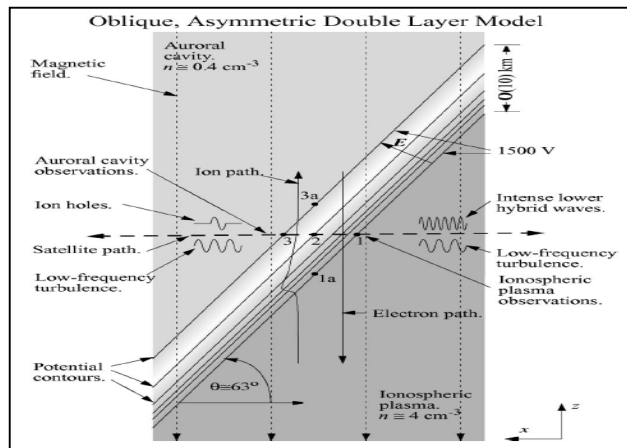
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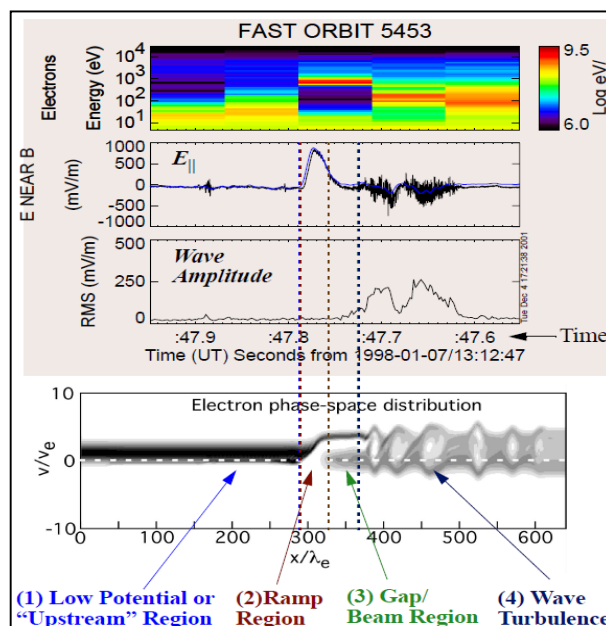
1456 **Fig. 2.1** Two-step evolution of the acceleration at substorm onset

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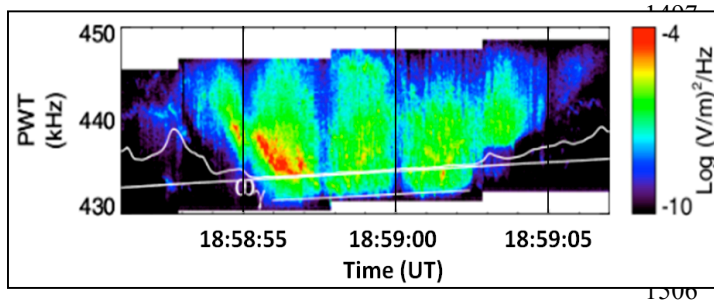


1473 **Fig. 2.2** Sketch of an oblique accelerating double layer and of its surrounding region [2.1].

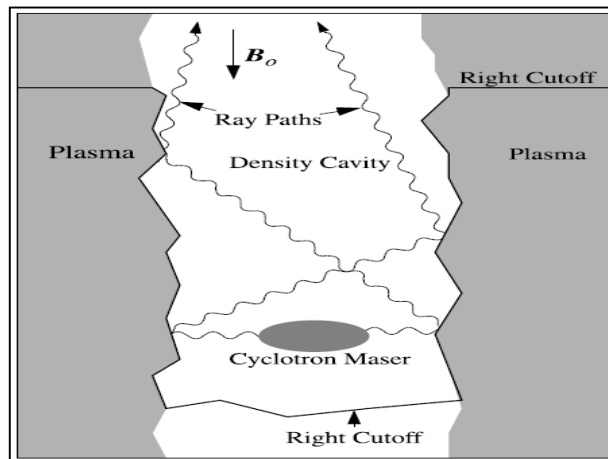
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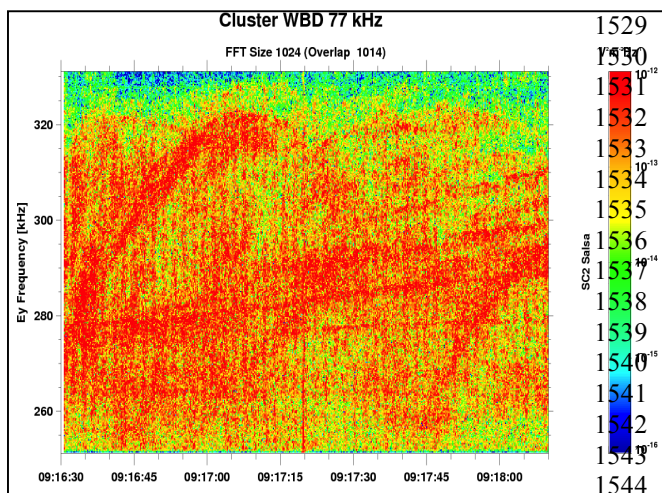
1496 **Fig. 2.3** FAST observations of DLs and wave turbulence, and numerical simulations [2.3].



1507 **Fig. 2.4** AKR FAST spectrum. The bold white line shows the electron gyrofrequency. The thin
 1508 white line shows the expected AKR cutoff [3.1].
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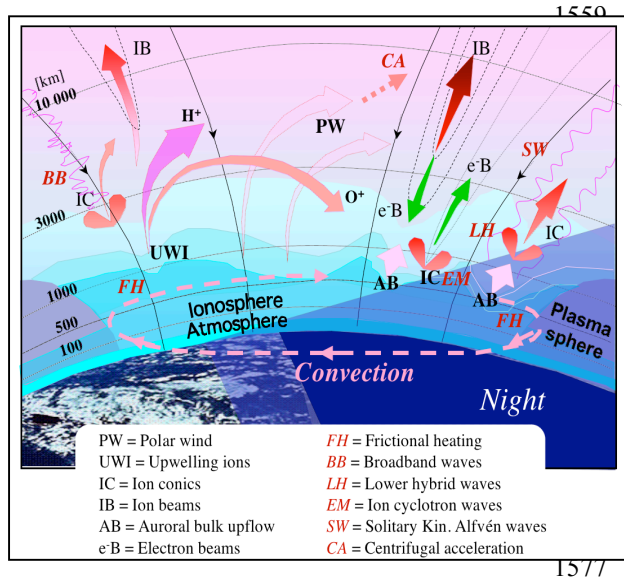


1525 **Fig. 2.5** Ray paths of AKR escaping from the auroral cavity [3.4].
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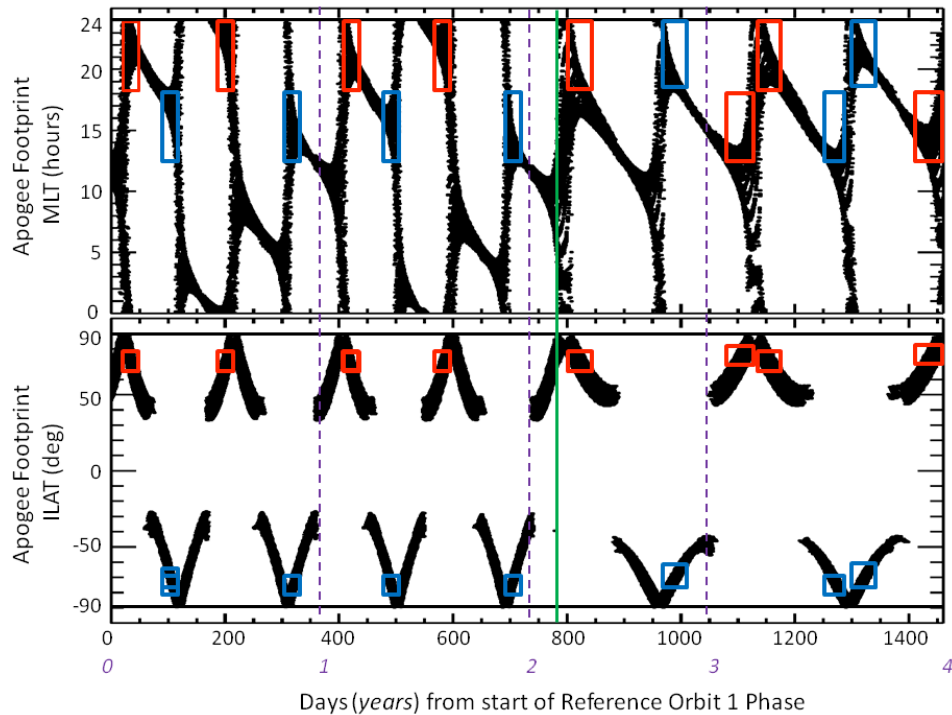


1545 **Fig. 2.6** Cluster observations of AKR fine structure (courtesy of J. Pickett).
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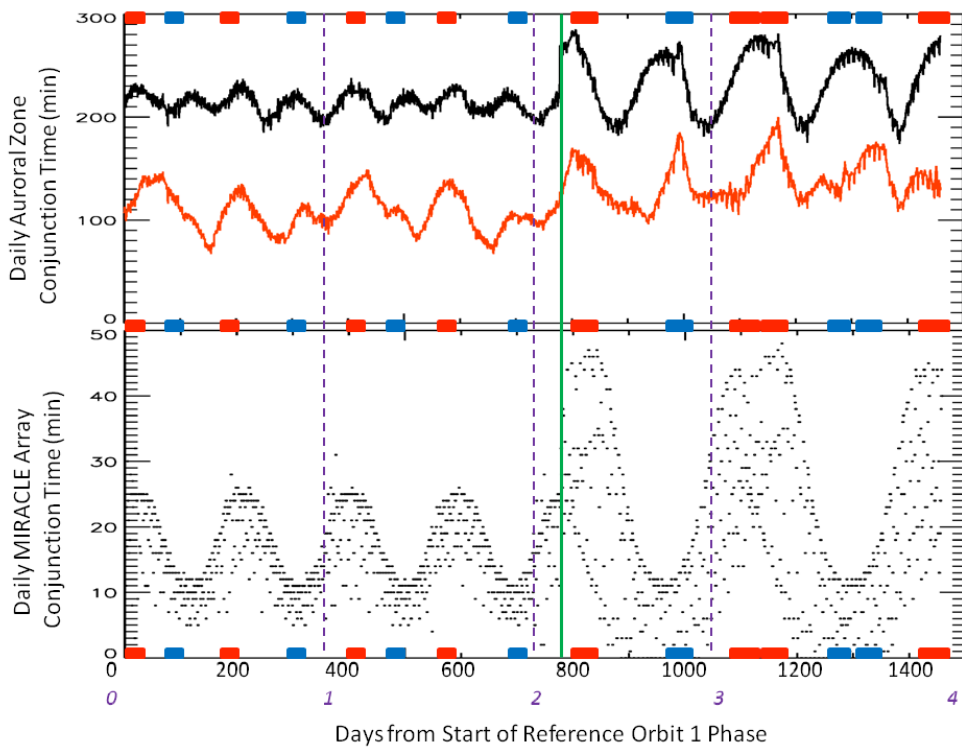


1578 **Fig. 2.7** Summary of ionospheric ion outflow related processes
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1619 **Fig. 3.1** Magnetic footprint coverage for times when the spacecraft are at apogee, for 4 years of
 1620 science operations. The green line at day 720 marks the transition from Ref Orbit 1 to Ref. Orbit 2.
 1621 Red (blue) boxes show intervals of good coverage in the northern (southern) hemisphere for the
 1622 MLT/ILAT regions with the highest probability of seeing accelerated auroral electrons. Cusp
 1623 observations are possible near 12 MLT at similar latitudes to those of the auroral observations.
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1625 **Fig. 3.2** Illustration of the daily accumulated time during which the spacecraft magnetic footprint
 1626 is in the auroral zone (upper panel) or over the MIRACLE array (lower panel), for 4 years of
 1627 science operations. As in Figure 3.1, red and blue markers show the target intervals, which in
 1628 general coincide with longer duration conjunctions, by design.
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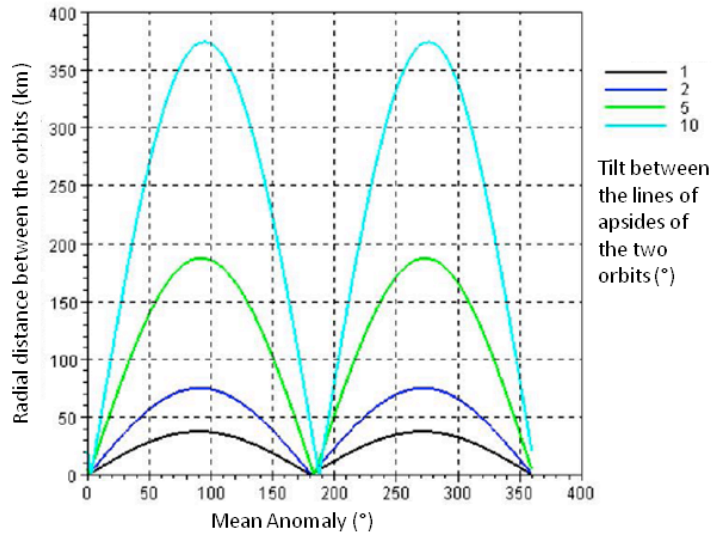


Fig. 3.3 Illustration of the variation with mean anomaly of the radial distance between two spacecraft on otherwise identical orbits, for which the angular separation of the lines of apsides are 1,2,5 or 10°.

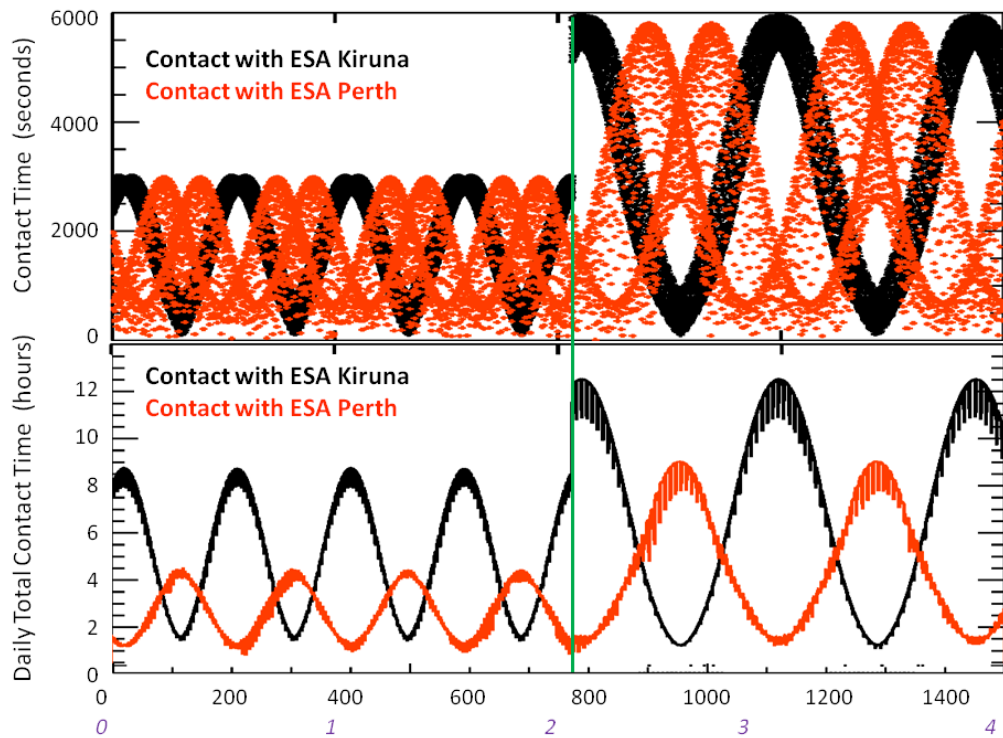
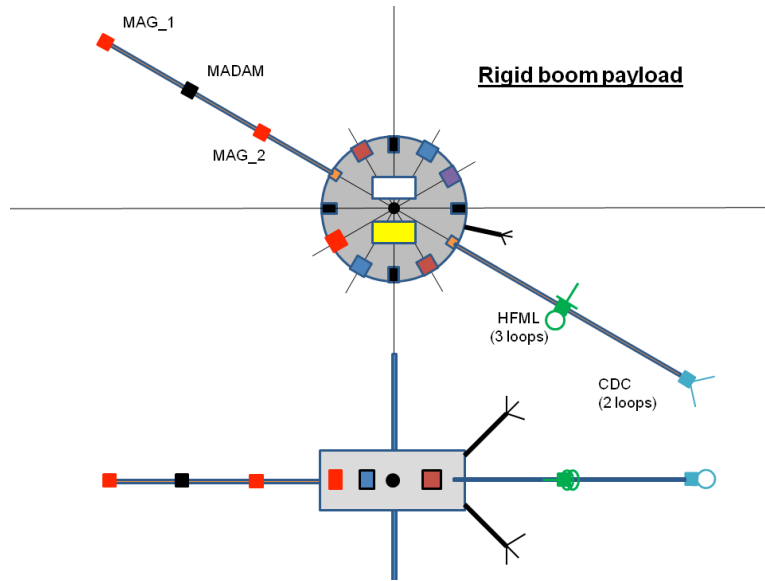
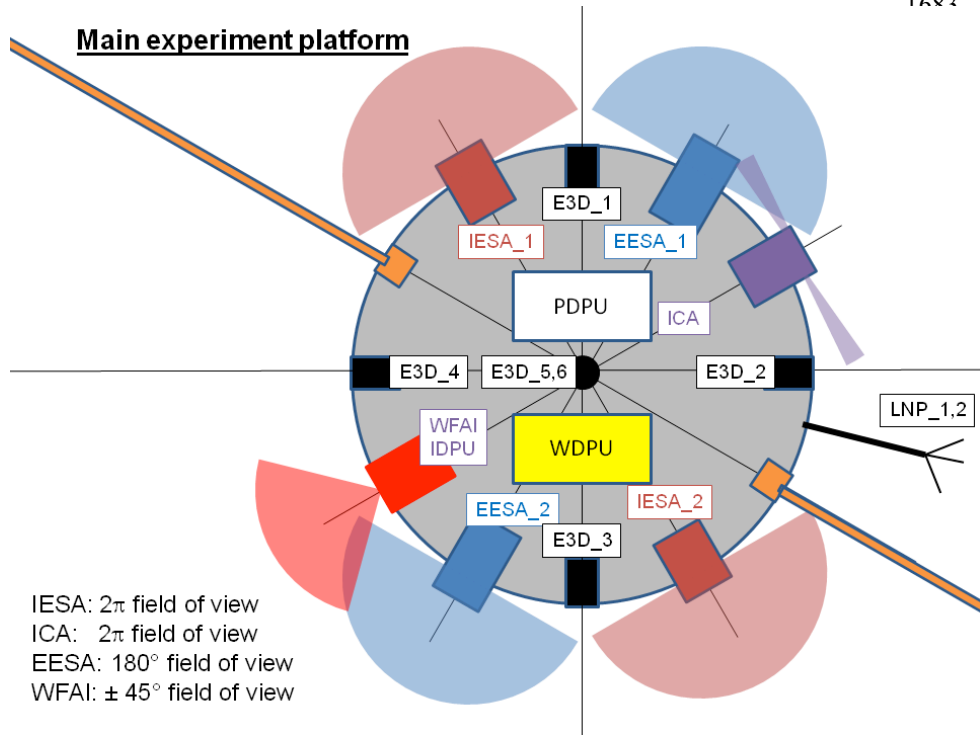


Fig. 3.4 Illustration of spacecraft-ground station access time, as the mission progresses. The upper panel shows the duration of contact times for each individual orbit, while the lower panel shows the accumulated daily total duration. Contacts with the northern hemisphere Kiruna station and the southern hemisphere Perth station are shown. It is clear that when one station has poor visibility of the spacecraft, the other can readily provide good coverage.



1681 **Fig. 4.2** Plan and elevation views of the spacecraft, illustrating the various booms and the
 1682 accommodation of the “fields” sensors

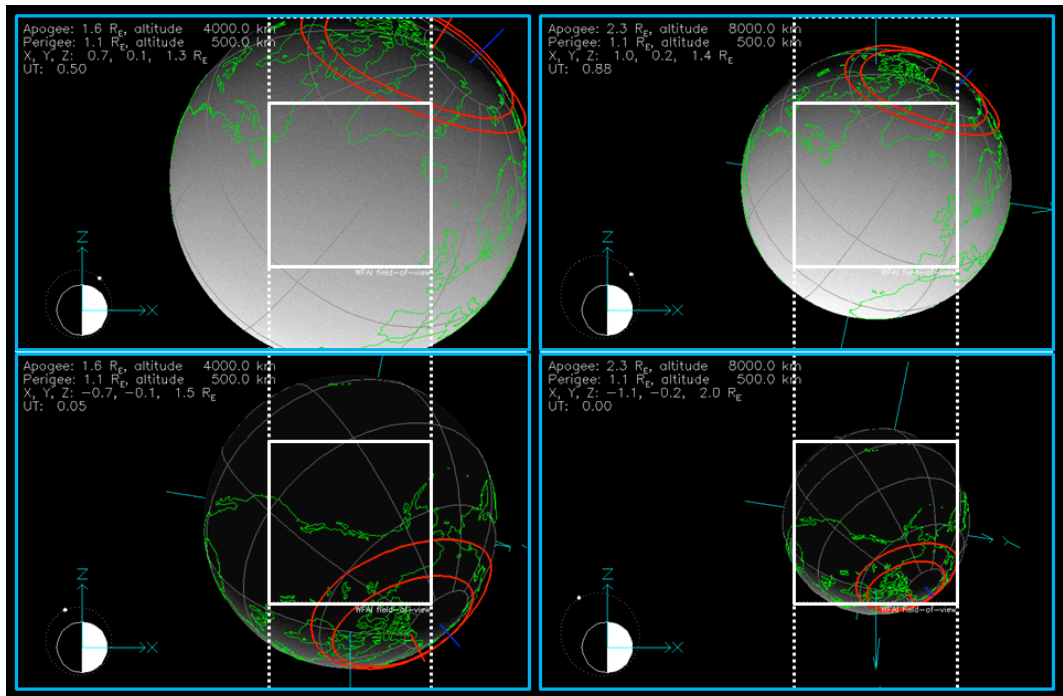
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1708 **Fig. 4.3** Plan view of the spacecraft main experiment platform, illustrating the accommodation of
 1709 the “particles” sensors, boom footings, auroral imager and data processing units.

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1726 **Fig 4.4** Illustration of the instantaneous and swept fields of view of WFAI with the spacecraft
 1727 crossing auroral magnetic field lines in the northern hemisphere, for an orbit with apogee at 60°
 1728 northern latitude. The left/right panels show the cases of Reference Orbits 1 /2, and the day/night
 1729 side of the Earth is shown in the top/bottom row. The solid white square is the instantaneous field
 1730 of view when pointing to the centre of the Earth. The dotted lines show the additional coverage
 1731 due to the rotation of WFAI with the spinning spacecraft.
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