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CROSS-SCALE

SCIENCE REQUIREMENTS DOCUMENT

Coordinated by/*préparé par*	C. P. Escoubet and S. Schwartz
written by	Cross-Scale Science Definition Team Petr Hellinger, Philippe Louarn, Rumi Nakamura, Chris Owen, Jean-Louis Pincon, Steve Schwartz, Luca Sorriso-Valvo, Andris Vaivads, Robert Wimmer-Schweingruber Masaki Fujimoto, Yoshifumi Saito (JAXA, ex-officio) Stuart Bale, Mona Kessel (NASA, ex-officio)
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European Space Agency
Agence spatiale européenne

ESTEC
Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
Tel. (49) 615190-0 - Fax (49) 615190 495 www.esa.int

The contents of this Science Requirements Document (Sci-RD) are agreed by all the contributors below to be the scientific requirements for the Cross-Scale mission against which the Reference Payload has been designed and the mission profile established.

Cross-Scale Science Study Team:

- Philippe Escoubet (Chair)
- Steve Schwartz (Co-Chair)
- Petr Hellinger,
- Philippe Louarn
- Rumi Nakamura
- Christopher J. Owen
- Jean-Louis Pincon
- Luca Sorriso-Valvo
- Andris Vaivads
- Robert Wimmer-Schweingruber
- Masaki Fujimoto (JAXA, ex-officio)
- Yoshifumi Saito (JAXA, ex-officio)
- Stuart Bale (NASA, ex-officio)
- Mona Kessel (NASA, ex-officio)

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1 INTRODUCTION

Most of the visible universe is in the highly ionised plasma state, and most of that plasma is collision free. Plasma processes are at work everywhere, from radio galaxy jets and supernova explosions to solar flares and planetary magnetospheres. Cross-Scale is an M-class mission dedicated to quantifying the coupling in plasmas between different physical scales. This cross-scale coupling, being highly variable and structured, is critical in underpinning and quantifying the physical mechanisms inferred to be occurring in plasmas that are difficult to observe.

As Astrophysical plasma regimes encounter each other, the absence of collisions raises fundamental questions about how energy is shared amongst the three main elements (electrons, ions, and overall bulk flows). These constituents, each of which operates on its own physical scale, are coupled through electromagnetic fields. Three fundamental physical processes operate to bring about the universal collisionless plasma coupling in physical environments where momentum and energy transfer is important:

- Shock waves guide fast flows around obstacles or at interfaces between two flow regimes. They are important locations for the transfer of directed bulk flow energy into heat, with an attendant acceleration of energetic particles.
- Magnetic reconnection releases stored magnetic energy to the plasma, and allows for exchange of material between previously isolated regions. Moreover, the consequent change in magnetic topologies provides a coupling between plasma regions which often drives the global scale dynamics of the system.
- Turbulence transports energy from large scales at which it is input to small scales where it is dissipated. In the process, it interacts strongly, and often selectively, with plasma particle populations as either a source or sink (or both) of energy.

Near-Earth space is a unique laboratory for quantifying the physics of these three processes. Breakthroughs have arisen due to the high quality of data that, unlike more distant regimes, is sampled directly by plasma and fields experiments on satellites. To date, in situ measurements have focused on terrestrial phenomena, such as the mechanisms that populate the van Allen belts. Dual spacecraft studies during the 1980's began to address the real microphysics. Present generation missions (Cluster and MMS) utilise 4 spacecraft to sample a specific volume, and hence characterise the physics operating on the single scale corresponding to the spacecraft separation. By the time MMS has flown, we shall have a catalogue of behaviour that ranges from the smallest, electron scale, to the largest fluid-like phenomena.

That knowledge is incomplete due to the ambiguity and uncertainty about the dynamics and variability of the larger contextual scales (for the electron and ion scales) and of the internal micro-processes that mediate the energy exchange (for the larger scales).

The complex, dynamic nonlinear coupling of scales and physical mechanisms cannot be quantified without simultaneous information on all scales. Cross-Scale will target compelling and fundamental questions, such as:

- **How do shocks accelerate and heat particles?**
- **How does reconnection convert magnetic energy?**
- **How does turbulence control transport in plasmas?**

These address directly the Cosmic Vision question “How does the Solar System work?” by studying basic processes occurring “From the Sun to the edge of the Solar System.” Moreover, by quantifying the fundamental plasma processes involved, the advances made by the mission will extend beyond the Solar System to plasmas elsewhere in the Universe.

Cross-Scale must employ at least 7 spacecraft possibly including two highly complementary spacecraft from its sister mission SCOPE provided by JAXA. Together, they will form nested tetrahedra to separate spatial and temporal variations simultaneously on the [three] key scales for the first time. The spacecraft, which carry a minimal payload with strong heritage, will be launched into a highly elliptical Earth orbit. Over the two year mission they will encounter various collisionless shocks, explore regions of both spontaneous and strongly-driven reconnection, and investigate both nascent and highly evolved plasma turbulence.

There are no technologies that need significant development or need to be proven for a launch in 2017, or earlier. The mission is thus low risk for high science return. It taps directly into European leadership in multi- point in situ space plasmas.

In the pages that follow, we amplify the universal science objectives and present a mature, concrete mission concept that fully meets these objectives.

In Chapter 2, the top-level scientific goals of the Cross-Scale mission are translated into specific scientific questions that in turn are used to derive the basic scientific requirements of the mission. Based on these scientific requirements, a concise quantification of the scientific quantities to be measured is given. In Chapter 3, summary tables then relate each instrument on each spacecraft directly to the science requirements.

2 SCIENTIFIC REQUIREMENTS

The Science Requirements for the Cross-Scale mission are varied and complex. For each main science question the text below describes through enumerated paragraphs and items the measurements that need to be made in order to answer the question. A matrix then collects this information into the required measurements at different scales, resolutions, cadences, and other aspects, and identifies the Cross-Scale instrument that will provide that measurement. A summary table then relates each instrument on each spacecraft directly to the science requirements. *[Measurements that are desirable and would greatly enhance the science return are given in italics and enclosed in square brackets. <u>Highly desirable requirements are underlined in addition</u>.]* These would be the first elements to be considered should resources above the current anticipated level (i.e. 7 or 5 s/c) become available.

Before we go into the detailed measurement requirements, let us consider how the various scales are determined.
Figure 2 shows the processes that Cross-Scale will study in different region of space in the near Earth's environment. Magnetic reconnection can be found in most regions from the low density lobes and plasma sheet regions to the high density shocked solar wind. Turbulence phenomena is also found in various regions, although the density of the plasma should be above 0.1 cm-3. Finally shocks are found mainly in the solar wind which has a more restricted range of temperature and density.

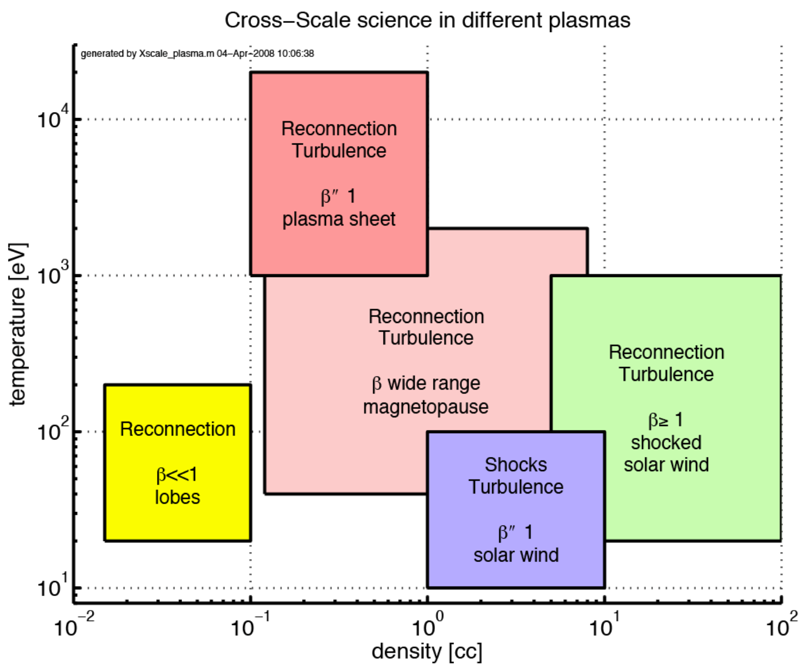

Figure2: Cross-Scale science objectives in different plasmas

Figure 3 gives us the various scale lengths and time scales present in near-Earth's environment. The smallest scales are the Debye length. Such scales are present when shocks are stabilized by charge separation or when strong plasma waves are generated. The electron diffusion region, in the reconnection process, is associated with the electron scale. The next larger scales are ion scales , that for instance size the plasma boundaries like bow shock, magnetopause and current sheet, and, ultimately, the largest -fluid- scale. The coupling between the various scales should be addressed by Cross-Scale by measuring at least two scales simultaneously.

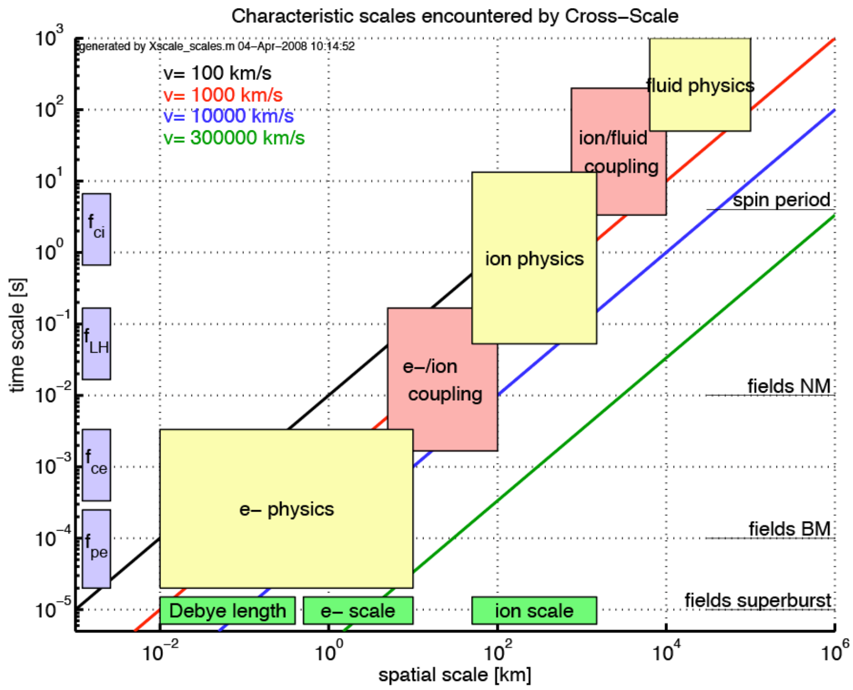

Figure 3: Characteristic scales to be studied by Cross-Scale.

2.1 SHOCKS

Collisionless plasma shocks are some of the most spectacular, visually striking and energetic events in the Universe. They occur when a supersonic flow hits an obstacle. At these locations, they deflect the incident plasma, thereby heating it, and in many cases accelerate particles to extraordinarily high energies. Collisionless shocks are essentially nonlinear three-dimensional time-variable structures which couple many different scales. The largest scale is determined by the global fluid motions. The bulk energy flowing into the shock is partitioned into various energy forms such as plasma heating and particle acceleration by poorly understood processes at smaller scales. Small-scale electron dynamics results in a highly structured, fluctuating electromagnetic field within the shock ramp. At scales around an order of magnitude larger, ions gyrate through the ramp, with trajectories determined by the fluctuating electron-scale electromagnetic field and by the larger scale electromagnetic field generated self consistently by these ions (e.g., waves/shock ripples, reformation), which in turn affects the small-scale dynamics of the electrons. This coupled multiscale structure allows collisionless shocks to heat the main plasma constituents as well as to accelerate sub-populations of ions and electrons to high energies. Acceleration is a part of the larger question about how shocks partition the bulk flow energy incident upon them, which again is effected over fluid, ion, and electron scales. Finally, variations in the flow that drives them, and instabilities within the transition scales, leads to transient phenomena that can significantly alter or enhance the acceleration efficiency.

2.1.1 S1 How do shocks accelerate particles?

2.1.1.1 S1a Shock parameters

Particle acceleration at shocks is poorly understood but generally believed to depend on the parameters of the shock such as orientation/geometry, Mach number, plasma conditions, and large-scale context/curvature.
Thus Cross-Scale must measure these parameters:

(i) Orientation/Geometry: The overall orientation is determined by the geometry of the inflowing plasma and the obstacle. Superposed on that are waves and ripples at smaller scales. Determining the orientation requires timing analysis, typically of the dc magnetic field, of features observed at a minimum of 4-points. The basic orientation is related to ion-scale dynamics which, in the solar wind, are typically ~1000 km at the Earth's bow shock and somewhat less at some interplanetary shocks. Thus magnetic fields from 4 s/c at 1000 km scales at a cadence ~ 0.5 s are required. Variability that is believed to play a critical role occurs on shorter scales, requiring 4 s/c timings at less than 100 km at 0.01 s cadence. *[The global orientation and curvature requires these together with 4-point measurements at scales > 10,000 km and timescales of 1s.]*

(ii) Plasma conditions including Mach number, density, speed, etc. and must be determined at two or more points at scales > 1000 km *[and preferably at 2 further points with an order of magnitude largerseparation at least for ions to be freer from shock contamination]*. Ion-timescales (~ a few seconds) set the cadence requirements at the bow shock so that the spin frequency is sufficient. Some interplanetary shocks would benefit from slightly faster measurements. Required plasma moments include density, bulk (proton) velocity, proton temperatures and anisotropies, and electron density, temperatures.

2.1.1.2 S1b Cross-Scale must measure the accelerated particles themselves.

(i) Cross-scale must measure 3D distributions both within and around the shock of suprathermal electrons and protons < 30 keV and lower energies (~few keV/charge) to include possible seed particles. Protons should be measured at 4 ion s/c at scales ~1000 km at cadences <=2 *s [2 more measurements at large scales > 5000 km are desirable to characterize the larger-scale context/variability]*. Electron acceleration within the shock layer requires measurements with cadences ~ 100 ms on 1 *[preferably 2]* s/c and one measurement separated from the first one (and from the shock) at ~1000 km with <= 2 s cadence.

(ii) Other ionic species, including alpha-particles and CNO ions participate to a greater or lesser extent in the acceleration process, and also serve due to their charge state to differentiate between particles of solar and magnetospheric origins. Moreover, their different m/q ratios serve as sensitive tracers for acceleration and injection processes. Measurements of these to 10's of keV/charge with some 3D distribution capability will address the acceleration of these particles. Measurement on at least one of the spacecraft is required at a cadence of 60 s.

(iii) The spectrum of accelerated particles at higher energies at both the bow shock and interplanetary shocks is of interest for astrophysical applications. Two measurements, one at electron and at least one at ion scales (separated by > 1000 km and *[also preferably larger scales]*), of proton and electron distributions to ~100 keV at the spin resolution or better would meet this requirement.

2.1.1.3 S1c The acceleration agents are the electric fields related to the shock.

(i) The primary shock structure is revealed in the dc magnetic field, which needs to be measured at 4 points separated by <100 km. Some characterisation of the full 3D electric field (to include the critical field parallel to the magnetic field) is required over the < 100 km shock layer together with adequate 2D electric field measurements at 4 locations to reveal the variability and extent of that field. Both these field measurements need a cadence ~ 0.01 s corresponding to a convected electron skin depth.

(ii) Turbulent and coherent higher frequency fluctuations probably play roles in the acceleration, scattering, and thermalisation of the particles. These include whistler electromagnetic disturbances well into the kHz range that probably are spatially structured on the smallest scales. Thus AC fields (2D electric and 3D magnetic) at 4 s/c separated by < 100 km with a typical cadence of 0.01 s are required. Two complementary measurements at > 1000 km with 0.1s cadence is needed to reveal how this turbulence couples to the escaping particles up- and downstream of the shock.

2.1.2 S2 How is the energy incident on a shock partitioned?

Shocks are complex structures where the incident energy must be dissipated at the same rate as it is fed into the shock. The dissipation within the shock and its structure are closely related. Both are known to depend on the parameters of the shock in question, thus Cross-Scale must determine its orientation, Mach number, plasma conditions *[and large-scale context/curvature]* as in S1a. However, the underlying processes (mainly particle acceleration and wave generation) may act on much smaller scales, and, hence, a solution of this problem must involve measurements at the smallest scales present in the shock.

2.1.2.1 S2a Cross-Scale must measure the energised particles themselves.

(i) 3D distributions of thermal and slightly suprathermal protons (of the order of 10 keV) must be measured in a way to resolve the reflected population at shock front scales with a cadence ≤ 2 s at 4 s/c with a separation ~<1000 km to measure its variability.

(ii) 3D distributions of thermal and slightly suprathermal electrons (of the order of 10 keV) ~ 0.1 s at (at least) 2 s/c with a separation ~<100 km to measure its variability.

(iii) 3D distributions of thermal and slightly suprathermal minor ions as alpha particles and CNO ions (of the order of 10 keV) must be measured at shock front scales with a cadence ~ 60 s on at least one s/c to address their energisation within the shock.

2.1.2.2 S2b Shock transition layer and waves

Most of the energy repartition is done within the shock transition, largely in a coherent manner (cross-shock potential jump and magnetic mirror force) and partially through wave-particle interactions

(i) Thus it is important to measure the shock 3D dc magnetic fields and their variability: for the ion scales dc magnetic field at separation <1000 km cadence 0.1 s at 4 s/c; for electron scales at a separation <100 km at 4 s/c cadence 0.01 s. Some characterisation of the full 3D electric field (to include the critical field parallel to the magnetic field) is required over the < 100 km shock layer together with adequate 2D electric field measurements at 4 locations with a separation <100 km at 4 s/c cadence 0.01 s and at 4 other locations with a separation <1000 km and at a cadence 0.1 s in order to reveal the variability and extent of that field on the two different scales.

(ii) In addition to dc features it is important to measure the wave activity (at least) 2D ac electric field and 3D ac magnetic fluctuations to few kHz in the vicinity of the shock front at 4 s/c at a separation <100 km, cadence 0.01s for the electron scales and at a separation ~ 1000 km for the ion scales, cadence 0.1 s.

2.1.3 S3 How do shock variability and reformation influence shock acceleration?

Strong shocks are fundamentally variable in time and space. They may exhibit reformation and/or rippled surface. Moreover, externally-driven variations can have profound effects on the shock dynamics. These effects result in a non-planar, and varying, shock profile, with important consequences for how particles are deflected, heated and accelerated. This internal variability (ripples, reformation, ...) is believed to depend on shock parameters. Thus Cross-Scale must determine its orientation, Mach number, plasma conditions *[and large-scale context/curvature]* as in S1a.

Cross-scale must measure the accelerated particles as in S1b.

2.1.3.1 S3a Cross-Scale must evidence the shock variability and reformation and must determine their properties

(i) To determine the shock variability/reformation and its properties it is important to measure the shock 3D dc magnetic profiles (including shock thickness): for ion scales dc magnetic field at separation <1000 km and cadence 0.1 s at 4 s/c and for electron scales at a separation <100 km at 4 s/c and cadence 0.01 s. Some characterisation of the full 3D electric field (to include the critical field parallel to the magnetic field) is required over the < 100 km shock layer together with adequate 2D electric field measurements at 4 locations with a separation <100 km at 4 s/c cadence 0.01 s and at 4 other locations with a separation <1000 km and cadence 0.1 s in order to reveal the variability and extent of that field on the two different scales.
[To investigate externally driven variations Cross-scale should measure 3D dc magnetic profiles at larger/fluid scales ~>10,000 km at 4 s/c and cadence 1 s]

(ii) To investigate the shock reformation it is important to measure the process of the proton reflection (including multiple reflection regions and/or regions with a strong accumulation of reflected protons): 3D distributions of thermal and slightly suprathermal (reflected) protons (of the order of 10 keV) must be measured in a way to resolve the variability of the reflected population at shock front scales with a cadence ≤ 2 s at 4 s/c with a separation ~<1000 km.

(iii) The shock variability/reformation may drive or may be driven by turbulent and coherent higher frequency fluctuations. Thus AC fields (2D electric and 3D magnetic) are required at 4 s/c separated by < 100 km with a typical cadence of 0.2 ms as well as measurements at 4 s/c at ≥ 1000km with 0.2 ms cadence to cover the electron and ion scales.

(iv) The shock variability (ripples) and reformation strongly affect electron dynamics within the shock (reflection/fast Fermi process, diffusion). Cross-scale must therefore measure 3D distribution of slightly suprathermal (as well as thermal) electrons (10 keV) with 0.1 s cadence at at least 2 s/c with a separation <= 100 km.

2.2 RECONNECTION

Magnetic reconnection is a fundamental plasma physics process which breaks down the barriers between neighbouring plasmas, releasing energy from their magnetic fields, transferring material and momentum between those plasmas, and accelerating a part of the plasma population to high energies. How such energy conversions take place is the key question to understand the reconnection process. Magnetic reconnection is expected to occur when magnetic fields are sheared across relatively thin current layers. In such current sheets, the kinetic effects of the particle populations become important, and the onset of reconnection is expected to occur on the distance and time scales of the relevant electron and ion gyromotions. Microscale processes can control the change of topology of the magnetic field, eventually affecting the large-scale plasma mixing and converting magnetic energy to plasma energy. On the other hand, large-scale (MHD) processes can control the location and formation of thin current sheets, and thus directly affect how reconnection initiates and evolves. It is therefore essential to follow both the large-scale and kinetic scale processes of the plasma to understand the onset, the evolution, and the result of the magnetic reconnection.

Cross Scale will for the first time cover the essential scales, namely electron, ion and *fluid scales* simultaneously to understand the way or ways in which reconnection arises, operates, and controls large scale dynamics. The near-Earth plasma environment is unique in that we can make detailed measurements for different types of current sheets, such as the large-scale Earth's magnetopause, tail neutral sheet, and solar wind discontinuities, or the more dynamic and small-scale current sheets in magnetosheath and within vortices at the magnetopause. Using relative motion of these boundaries to the spacecraft and optimizing spacecraft configuration and instrumentation, Cross-Scale allows, for the first time, the study of the multi-scale processes involved in reconnection and the ways in which they are coupled.

Specific top-level scientific questions and the associated measurement requirements of relevance to those goals are as follows.

2.2.1 R1 What initiates magnetic reconnection?

In order for magnetic reconnection to occur, a region must exist in which the magnetic field can diffuse relative to the plasma and across the current sheet separating two plasma regimes. According to present theory, a precondition for reconnection is that the current sheet must undergo a thinning process. We do not know, however, why reconnection may begin at a particular point in a thin current sheet and not at a neighboring location. In order to fully characterise the development of thinning of pre-reconnection current sheets we must use a set of multi-point observations across *at least three scale sizes*, each optimized to capture a different stage in the thinning process. Multi-point spacecraft with the largest separations will provide information about the total magnetic flux change across the current sheet, and about the orientation of the current sheet, through which all other observations can be put into context. These spacecraft also obtain the external conditions, such as the driving electric field or shear angle outside the current layer. The spacecraft with smaller separation will then measure the intensification and thinning of current within the overall sheet structure, and also provide information on the internal variations in plasma characteristics to determine how such currents are supported.

2.2.1.1 R1a Cross-Scale must follow changes of current sheet

Cross-Scale must follow changes of current sheet (thickness, orientation, internal structures) leading to reconnection and needs to identify the critical thickness of the current sheet at which reconnection starts. *[Simultaneous knowledge of the large-scale condition outside the ion current sheet is also highly desirable.]*

(i) Orientation of the current sheet requires timing analysis on features observed by at least 4-point measurements of typically the dc magnetic field. It is believed, but not yet proven, that electron scale processes in the ion-scale current sheet are responsible for growth of the reconnection rate. Thus, accurate quantification of the current sheet at the ion scale and resolving the embedded electron-scale current layer, both with 4-point measurements at 5-50 km studying the electron scale and 100-500 km studying the ion scale, are required. The required cadence for these observations are 0.02s. *[Thinning of the current sheet starts from MHD-scale current sheet, and determining the orientation of this is desirable, which requires multi-point observations at least at two points. Four points would further allow a determination of the orientation of the tilted or oscillating large-scale current sheet, which will provide more accurate 3D information. Appropriate separations of the spacecraft for studying these large scale phenomena is 5000-15000 km and cadence is spin frequency]*

(ii) Plasma and field condition of the current sheet
The critical spatial scales of the current sheet measured with the multi-point magnetic field measurements in (i) must be compared with the plasma parameters, such as the ion and electron gyro-scales and the inertial lengths, in order to specify the underlying mechanisms. This requires also understanding of the observed temporal changes with respect to the different time-scales of the plasma motion, such as Alfven travel time, ion and electron gyro- and plasma-frequencies. Moment data of plasmas with a cadence of ~2s, comparable with the typical observation time of an ion current sheet, are required at multiple points (at least 2) separated by 100-500 km, a spatial scale comparable to the ion current sheet *[It is desirable to cover simultaneously the outflow and inflow region, requiring at least 2-point ion plasma measurement with cadence of spin period also at fluid-scale separation, 5000-15000 km]*.

2.2.1.2 R1b Cross-Scale must detect the onset signatures of reconnection.

Signatures of reconnection onset can be detected as sudden appearance of accelerated plasma, enhanced field disturbance associated with change in the field topology as given below. Observation capabilities detecting at least one of these signatures are required. Same as for R1a, multi-point observations at electron, ion, and *[fluid scale]* requires spacecraft separation of 5-50 km, 100-500km, and *[5000-15000 km]*.

(i) Enhanced reconnection/parallel electric fields and signatures of reconnected magnetic flux should be detected by DC E and DC B measurements. [*3D electric field measurements are desirable on the electron scale.]* In order to distinguish the electric field components with respect to the ambient fields and the thin current layer, simultaneous 4-point measurements of DC B and at least 2-point measurements of DCE at electron scale are required. Understanding the reconnection geometry requires 4-point measurement of the DC B, while measurement of the temporal/spatial development of the reconnection electric field requires at least 2-point measurements of the DC E field on the ion-scale. These DCE and DCB measurements require cadence of 0.02 s.

(ii) Enhanced higher frequency fluctuations are expected around reconnection onset time, when turbulence caused by instabilities may produce enhanced anomalous resistivity, or waves interacting with electrons lead to the growth of instabilities. These electromagnetic disturbances are probably spatially structured on the smallest scales relating to the electron physics. Thus AC fields (2D electric and 3D magnetic), up to kHz (cadence of 1 ms) in AC B and 100 kHz (cadence of 0.01ms) in AC E, are required to be measured. In order to obtain the distribution of such fluctuations relevant to the electron-scale signatures distributed in the ion current sheet, 4-point observations for both electron and ion scale are required for AC B. At least 2-point observations at both scales are required for AC E.

(iii) The existence of fast ion flows or ions accelerated at a slow-shock are also evidence of ongoing reconnection, while unmagnetized ion particle behaviour suggests also the development of thin current sheets which can lead to reconnection. Hence, 3D distributions of ions < 30keV are required at least with cadence of 2 s to obtain moments at *≥2 points* on the ion scale *[and desirable at ≥2 points on the fluid scale with cadence of spin period].*

(iv) Electron behaviour such as existence of accelerated meandering electrons, agyrotropy or temperature anisotropy Te_{perp}/Te_{para} in the electron scale current layer must be resolved since they affect the growth of instabilities leading to reconnection. Measurements of 3D distributions of electrons < 30keV with cadence of 50Hz are required on ≥1 spacecraft to provide several complete distribution functions during a typical crossing time of an electron scale current layer, i.e. ~0.1 s, and to allow comparison with wave activities such LHD waves *[Since the growth of the reconnection rate will take place within of order several ion gyro times, comparable to the time-scale of crossing of an ion-scale current sheet, ≥2 spacecraft measuring 3D distributions of electrons < 30keV with at least 10 Hz cadence separated at electron or ion-scale will enable the detection of the temporal/spatial evolution of the instability].*

2.2.1.3 R1c Cross-Scale must specify the large-scale/environmental conditions resulting in reconnection.

[Reconnection is observed to take place within different types of current sheet. Covering these different parameter regimes will serve to understand what parameters triggers the reconnection onset.

(i) Large-scale conditions such as the temporal change in the driving electric field, shear in the magnetic field, large-scale gradient in the density or magnetic field across and along the current sheet are expected to modify the reconnection current geometry and the reconnection rate. Although the satellite motion across the current sheet may provide a hint of the large-scale conditions, simultaneous monitoring of these conditions is desirable in order to understand the response of the system to the various driving conditions. At least 2 point measurements of the DC magnetic field and ion density and flow measurements, at a cadence of spin period and with separation of >5000 km, are desirable to obtain these large-scale gradients. Furthermore, 4-point measurements would increase the probability of successfully monitoring simultaneously the gradients in the inflow and outflow region and thereby understanding the large-scale context in 3D.

(ii) Other ionic species, in particular Oxygen ions can also modify the dimension and structure of the current sheet and thereby change the reconnection rate. Nevertheless, reconnection signatures have also been observed without significant Oxygen ion content. Oxygen ions can serve to differentiate between particles of solar and magnetospheric origins. Measurements of charge state for <30 keV ions at a cadence of spin period from at least one of the spacecraft are highly desirable to address these environmental conditions, i.e., whether the analysis of events needs to take account of the contribution from O xygen ions.]

2.2.2 How does the magnetic topology evolve?

A major consequence of the reconnection process is that localized changes in the magnetic field topology (magnetic fields are "reconnected") leads to release of magnetic field energy across large regions of space. Understanding how the small-scale controlling influences of reconnection relate to the results of reconnection and its control of the global environment is particular important if we wish to extrapolate our results to other planetary, solar or astrophysical systems in which the parameter regimes may be widely different. Once magnetic reconnection has begun, there are many questions about how it is maintained. Reconnection in the solar wind can endure for hours; at the magnetopause, it can be either similarly persistent or very bursty on a timescale of minutes; in the magnetotail reconnection seems more often to last only minutes or tens of minutes. However, these time-scales are all long compared to typical electron and ion time-scales, showing that reconnection can operate in a quasi-steady state, relative to the time-scale of the kinetic processes that are thought to sustain it.

2.2.2.1 R2a Cross-Scale must follow the temporal and spatial evolution of the 3D geometry of the reconnecting current sheet after onset:

(i) Topology changes are either due to parallel electric fields or due to magnetic flux transport through magnetic null points (lines). Thus the measurement of high quality 3D electric and magnetic field vectors is crucial to understanding of topology changes; we need small spacecraft separations and high cadence measurements as the strongest parallel electric fields typically appear on the electron scales. This objective requires DCB measurements at 4 s/c on the electron scale (separated by distances in the range of 5-50 km) and 3D electric field measurements from at least one of the spacecraft (could be SCOPE) covering that scale. The required cadence for both these sets of measurements is 50 Hz.

(ii) It is important to determine the distribution of parallel electric field with distance from a reconnection site to assess whether, or by how much, this field contributes to the topology changes; parallel electric fields can extend far from reconnection site along e.g. separatrix regions and thus electric field measurements from spacecraft with large separations are also desirable. It is also important to determine the variation of the electric field along the magnetic neutral line. This objective requires DC B measurements at ≥2 s/c on the ion scale (separated by distances in the range of 100-500 km) and 2D electric field measurements from ≥2 spacecraft covering that scale. The required cadence for both these sets of measurements is also 50 Hz. [*Furthermore it would be desirable to extend these measurements to the fluid scale (5000-15000 km separations) where DC B and 2D DC E measurements should be made at ~ spin resolution (~4 seconds) on ≥2 spacecraft.]*

2.2.2.2 R2b Cross-Scale must identify the different regions (electron and ion diffusion regions, the magnetic separatrix, etc.) on the different scale lengths:

(i) Identification of the electron diffusion region and its spatial extent requires the ability to identify where the electrons are demagnetized. This implies high quality electron velocity moments from at least 1 spacecraft at a cadence of 50 Hz which must be compared with the 3D electric field drift velocity derived from DCB and DCE measurements and determined at the same rate. Electron acceleration in the weakening magnetic field close to the magnetic null point may also be a signature of this region and identification of this requires similarly high resolution measurements. [*Determining the extent of the electron diffusion region implies these measurements are simultaneously available from at least 2 spacecraft on the electron scale.]*

(ii) Similarly, identification of the ion diffusion region and its spatial extent requires the ability to identify where ions are demagnetised while electrons remain 'frozen-in' to the magnetic field. Again this requires high quality electron and ion velocity moments, derived from the 3D velocity distribution functions of these particles, to be available at 1 sec time resolution from at least 1 spacecraft *[desirable at least 2 s]* on the ion scale (separation 100-500 km) for comparison with the 3D electric field drift velocity. [*Determining the extent of the ion diffusion region implies these measurements are simultaneously available from at least 2 spacecraft on the ion scale and ideally at least one further spacecraft on the fluid scale (where lower time resolution, spin period, is also acceptable).]* Relative motion of the ion and electron populations, with electron drifts in the direction of the reconnection electric fields, need to be determined in order to identify any 'Hall current' systems in the ion diffusion region, which can be compared to the expected quadrupolar deflections of the magnetic field and the 'Hall electric field' opposing the charge separation. Identification of the 'Hall current' system using magnetic field meaurements requires these measurements to be made at 4 points on the ion scale, obtained with 1 second time resolution.

(iii) Very little information is available about the electron diffusion region. In order to test ideas about how the diffusion occurs, Cross-Scale must measure the contribution to the reconnection electric field made by very small-scale phenomena including non-gyrotropic electron pressure anisotropies or bulk electron flow anti-parallel to the main current. However, reliable data on particle behaviour in the electron diffusion region requires better time resolution than has previously been flown. In addition, we also need to identify any waves which may scatter and demagnetise electrons in and around their diffusion region. For example, whistler mode wave activity in the diffusion region may enable more efficient reconnection. This objective requires that very high time resolution (~20 ms) 3D electron distributions be measured on at least 1 spacecraft on the electron scale, for comparison with AC magnetic and electric fields, which should have time resolutions capable of identifying relevant wave modes (0.1 and 0.01 ms respectively).

(iv) Open/closed field line boundaries can be identified through the changes in the electron distributions. High temporal resolution (20 ms) electron distribution measurements from at least 2 spacecraft would also enable an estimation of the local speed of the open/closed boundary, and thus the reconnection rate. [*Observations of this boundary on ion scales with cadence of 1s from at least 2 spacecraft are needed to identify the formation of multiple X-lines or new X-line formations within the system*.]

2.2.2.3 R2c Cross-Scale must monitor the environmental context of the current sheet.

[(i) In general, reconnection topologies are more complicated than the simple 2D picture. In particular, the large scale magnetic fields at the magnetopause are often sheared across the current sheet, such that there is a component along the direction of the reconnection electric field. Many numerical simulations have demonstrated how this "guide field" scenario might differ from the simpler 2D case, but the physics of these models cannot be tested without observations of the magnetic field at spin resolution (~4 secs) by the 4 spacecraft covering the fluid-scale to provide boundary conditions simultaneously with the measurements discussed above.

(ii) Other departures from the symmetrical 2D picture that need to be examined include the differences in flow velocity, plasma density and temperature across the current sheet. Thus Cross-Scale plasma measurements on the larger fluid scales are also needed to reveal, for example, the differences in the way reconnection works at the magnetopause in comparison to the magnetotail. At least 2 point measurements of the DC magnetic field, ion densities and flow measurements at a cadence of spin period are desirable to obtain these large-scale gradient with separation of >5000 km. 4 point measurements further increase the probability of simultaneously monitoring the inflow and outflow regions and thereby understanding the large scale context in 3D.

(iii) Similarly, comparisons of magnetotail reconnection with and without significant oxygen ion populations are needed to test models of how the current sheet structure and reconnection rate depends on their plasma composition. It would be expected that an additional scale associated with oxygen gyroradii will play a role in controlling the reconnection process in this case. Measurements of charge state for <30 keV ions at a cadence of spin period from at least one of the Cross Scale spacecraft will address these environmental condition, i.e., whether the analysis of events need to take into account contribution from Oxygen-ions.]

2.2.2.4 R2d Cross-Scale must determine the role of reconnection in the dissipation within turbulent plasma regions.

In this case, the change in the magnetic topology due to reconnection is even more difficult to analyse. Same as the other requirements of reconnection given before, multi-point observations at electron, ion, and *[fluid/large scale]* requires spacecraft separation of 5-50 km, 100-500km, and *[5000-15000 km]*.

(i) Turbulence can develop at plasma boundaries (such as vortices at the magnetopause). Cross-scale must identify changes in topology due to reconnection through changes in the plasma distributions resulting from direct plasma transport across the boundaries and the formation of a boundary layer. [*Thus multi-point ion distribution measurements (~4s or spin resolution) from at least 2 spacecraft are desirable on a large scale to monitor the boundary layer development]* and from at least 2 spacecraft on smaller ion scales to understand the reconnection mechanisms. Similarly, electron distribution measurements from at least two spacecraft are required to be made simultaneously on both ion and electron separation spacecraft at the appropriate resolution (~1 sec and 20 msec respectively).

(ii) In other situations, such as in the magnetosheath, the plasma is turbulent across a large volume, and magnetic islands and other coherent magnetic structures can continuously form and disappear due to reconnection. [*Spacecraft at large separation would be able to follow the development of these structures]*, while small separation spacecraft would be able to follow the physics of reconnection process itself. This objective requires 4-point magnetic field measurements at 1 sec resolution on the ion scale *[while 4-point measurements at spin resolution on the fluid scale are also desirable]*.

2.2.3 How does reconnection accelerate particles and heat plasma?

Reconnection most probably occurs in a wide variety of contexts beyond the Earth's magnetosphere; most can only be studied by remote sensing of the emissions generated indirectly by energetic particles. For example, X-rays generated during solar flares. Even in the magnetosphere, energised particles measured in situ are often the only sign of a distant reconnection site. In order to interpret such data as reconnection signatures or otherwise, and perhaps to use them to infer the properties of the reconnection site itself, we must understand how particles are accelerated and heated. It is also important for understanding the efficiency of reconnection as a contributor to the generation of energetic particles in the plasma of universe. Most of the energy released during the reconnection process goes into the energisation of ions and electrons. Observations show evidence of reconnection outflow jets and particle heating, and of the formation of field-aligned beams and energetic tails in the particle distributions. However, their origin is not understood in detail. Earlier measurements and numerical simulations suggest that much of the energization happens at the boundaries and near the reconnection site but also other regions are important such as reconnection jet outflow region, turbulent regions, secondary islands, etc, Different processes at different scales can operate at the same time and they in addition depend on the boundary conditions near the reconnection site. Local electric and magnetic fields in 3-dimensions and particle data for a broad range of energies at high time resolution are needed to infer where in the system the acceleration occurs.

2.2.3.1 R3a Cross-Scale must follow the orientation of the reconnection site, the orientation and speed of filamentary current sheets and density gradients.

Also it is important to know the plasma conditions (including magnetic field orientation) in the inflow region *[and large-scale context such as presence of the multiple X-lines, the extension of the X-line or large magnetic obstacles in the reconnection jet outflow directions].*

(i) The orientation of reconnection site, current sheets and large scale density gradients requires timing analysis on features of magnetic field and plasma density observed by at least 4-point measurements separated at ion scales. To resolve those scales requires the cadence of 0.02 s [is it plasma density and magnetic field?, if yes, is the plasma density coming from the spacecraft potential?]. The current sheet filaments and density gradients where significant particle energization can take place can be on a few times electron scales and therefore require 4 s/c timing of magnetic field and plasma density on electron scales and with at least 0.01 s cadence. (Note that by assuming quasi-neutrality, for density estimates at least one s/c requires fast electron instrument but the others s/c requires only sounder or proxy values from spacecraft potential for fast density measurements) *[The large scale context requires these together with multiple measurements at scales > 5,000 km.]*

(ii) Particle acceleration mechanisms can depend on the initial and boundary conditions during the reconnection. Thus the presence of a guide field can change the situation from electrons being unmagnetized to being magnetized near the X-line leading to different acceleration processes. Also the cold and pre-accelerated particles in the inflow region can follow different energization mechanisms. Plasma conditions and magnetic fields need to be characterised on both sides of the current sheet and require at least two point measurements on ion scales *[and preferably also at more than 2 points separated by larger scales, 5000 -15000 km, to see ion plasma conditions in inflow region undisturbed by the reconnection site]*. For the observations at ion scales, it is sufficient to resolve the plasma conditions at a cadence of 2s - a few times characteristic ion-time scales and is required to measure both ion (proton) and electron 3D distribution functions. *[For the observations at larger scales, 5000 -15000 km, cadence with spin period is desirable].*

2.2.3.2 R3b Cross-Scale must measure the accelerated particles themselves.

It is important to understand both the acceleration of plasma, the heating of plasma and particle energization to suprathermal energies (high energy tails of distribution functions). The energization in most cases is anisotropic process thus it is necessary to obtain full distribution functions.

(i) Most of the magnetic energy during magnetic reconnection is converted into the acceleration of plasma bulk flows and plasma heating. To observe those processes requires measurements of 3D distribution functions of electrons and protons < 30keV and their moments (density, velocity, temperature) measured both within and around the reconnection site. Much of the ion heating and ion flow acceleration can occur in regions that are comparable or larger than characteristic ion scales, as for example rotational discontinuities at the magnetopause, but in other situation much of the acceleration can occur on scales that are fraction of characteristic ions scales, as for example observed in magnetotail. This requires that at least 2 s/c on ion scale separation resolve 3D ion distributions with 2s cadence *[and at least 2 s/c on fluid scale separation with cadence of spin period]*. While obtaining the 3D distribution with 2s resolution, it is required that a part (2D slice) of the ion distribution to be obtained with cadence of 0.5s for at least at one s/c. A large part of electron acceleration within the diffusion region and inside the separatrix region occurs on characteristic electron spatial scales and lower hybrid temporal scales. Therefore, resolving electrons accelerated at those scales requires 3D distributions with cadences ~20 ms on 1 *[preferably 2]* s/c. To see the electron acceleration across the boundaries requires simultaneous observations of 3D distribution functions on at least 2 s/c at electron [*and 2 s/c on ion scales]* at cadence of 2s for the entire 3D distribution, with part (2D slice) of the electron distribution to be obtained with cadence of 0.1s.

(ii) The acceleration process is different for different ion species and therefore its both important to identify different ion species both studying only protons to be sure there is no contamination from other species as well as studying acceleration processes of different ion species. [*Measurements of He and CNO to 30 keV/charge with some 3D distribution capability would be desirable.]*

(iii) The distribution functions at energies five and more times the thermal energies inside the reconnection sites is of particular importance for astrophysical applications. Observations show, and numerical simulations support this result, that significant changes in the distribution function of most energetic particles can occur on relatively short spatial scales comparable to the characteristic inertial scales of that population. This requires measurements of proton distributions to at least 200keV [*preferentially at 2 locations separated on fluid scale]* at cadence of spin period and electron distributions to at least 200 keV [*preferentially at 2 locations separated on ion scale*] at cadence of spin period. While obtaining the 3D distribution with spin period resolution, it is required that a part (2D slice) of the electron distribution to be obtained with cadence of 0.5s.

2.2.3.3 R3c Cross-Scale must identify plasma waves, DC fields associated with Hall physics, reconnection fields, inductive fields, etc. that can be responsible for particle acceleration.

Cross-Scale must also resolve the orientation of those fields with respect to the reconnection site, local boundaries and local ambient magnetic field.

(i) The primary structure of reconnection site and current layers where acceleration is ongoing is revealed in the DC magnetic field, which needs to be measured at 4 points separated on ion scale at 50 Hz sampling rate. In addition, adequate 2D electric field measurements on at least 3 locations on ion scale are needed to reveal the variability and extent of that field (usually electric field has negligible parallel component on these scales and therefore 3 locations are sufficient). Multi-spacecraft measurements of magnetic fields can allow also measurements of weak inductive electric fields that can be difficult to measure directly but which can play an important role in creating energetic tails in particle distributions. The cadence of both electric and magnetic fields should be at least 0,02s to resolve convected Hall scales (scales in-between electron and ion scales), at these scales typically strong localized electric fields, responsible for significant ion acceleration, are observed. Similarly, to resolve the electron scale fields requires at least 4 point DC magnetic field measurements at cadence 0,01s (to resolve convected electron skin depth and lower hybrid frequency waves) and at least 3 point 2D electric field measurement at the same cadence. Some characterisation of the full 3D electric field (to include the critical field parallel to the magnetic field) is required over the electron scale volume.

(ii) Higher frequency fluctuations play a large role in the energization and scattering of electrons. These include, for example, whistler electromagnetic disturbances well into the kHz range that probably are spatially structured on the smallest scales as well as electron plasma frequency waves, electron holes and double layers. All these waves cover scales from electron scales up to scales close to ion scales. It is also important to distinguish between electrostatic and electromagnetic plasma waves. This requires AC field measurements of 2D electric and 3D magnetic fields. Magnetic fields are required at 4 s/c separated on electron scales and 4 s/c on ion scales with a typical sampling frequency ~1kHz (cadence of 1 ms), covering electron gyrofrequency. Electric fields should be measured on at least 3 s/c at electron and 3 s/c on ion scales at sampling frequencies ~100kHz (cadence of 0.01 ms), covering plasma frequency. Some characterisation of the full 3D electric field (to include the critical field parallel to the magnetic field) is required over the electron scale volume. [*ACE and ACB measurement separated with fluid scales from the other measurement points and with the same cadence to the other ACE/ACB observations is needed to reveal the spatial development of wave-particle interaction*].

2.3 TURBULENCE

2.3.1 T1 How does the turbulence cascade transfer energy across physical scales?

2.3.1.1 T1a Description of the spectral properties of the turbulent cascade

The description of the spectral properties of the turbulent cascade is needed to understand the phenomena occurring at different scales and the transition between plasma regimes (MHD, Hall-MHD, kinetic…). Cross-Scale must determine, through the k-filtering technique, the 3D full spectra of the field energy and magnetic helicity in (w,k) domain. These are obtained from the spectral properties of magnetic and electric fields. To fully characterize the turbulent cascade, the kinetic energy distribution of both ions and electrons across physical scales is also required. This is obtained from the spectral properties of ions and electrons moments.

(i) The determination of the 3D field energy distribution in frequency and wave vector domain requires the time series of AC and DC magnetic (3D) and electric (2D) fields at 4-point for any scale in the cascade. Investigation of the dispersive/dissipative scale makes it necessary to cover an appropriate frequency domain with appropriate distances between the spacecraft. Typical spectral breaks are expected to be found around the ion and electron physical scales so that measurements are needed with spacecraft distances in the ranges *[~10000 km]*, ~1000 km, and ~100 km. A frequency range up to 200 Hz is a minimum to take into account whistler modes waves/structures.

(ii) The determination of the 3D kinetic energy distribution in frequency and wave vector requires the time series of the ion and electron moments (density and velocity) for any scale in the cascade. Investigation of the dispersive/dissipative scale makes it necessary to cover the ion and electron physical scales so that measurements are needed with spacecraft distances in the ranges *[~10000 km]*, ~1000 km, and ~100 km. Electrons should be measured simultaneously with the best time resolution (better than 10Hz) at the electron scale, at least on 2 spacecraft. *[High resolution electron measurements at 4 spacecraft are useful but not mandatory].* Ion distributions should be measured with 2 second time resolution or better at the ion scale (4 spacecraft). Higher time resolution (~ 1 Hz) ion distribution functions are required on at least one spacecraft. [*At the fluid scale, a lower time resolution measurements (typically the spin period) for both electron and ion measurements is sufficient to give evidence for the injection scale.]*

(iii) Inaccuracy in the time synchronization and the knowledge of the vector separation between different spacecraft can distort the field energy and kinetic energy spectra estimation. To limit these effects, the relative time accuracy between all S/C has to be less than 0.1ms. Similarly the separation vector distance between all S/C has to be known with a precision of 5% regarding the magnitude and about 10° regarding the direction.

2.3.1.2 T1b Partition of energy between particles and waves

Recent theoretical work on Hall-MHD turbulence show that non local interactions occur when a departure from equipartition between kinetic and magnetic energies is observed. Obviously the partition of energy between particles and waves is a crucial question. Collisionless plasmas can support several eigenmodes of energy propagation, developing at different scales. These modes determine the properties of the transport, and the changes in the magnetic topology. Excitation of waves is indeed responsible for the dissipation (or storage) of part of the energy cascading toward the small scales. Cross-Scale must provide the relation dispersion for wave modes present in plasma, and the field energy associated with these modes will have to be compared with the total energy cascading at each scale. Because of the importance of anisotropy effects, the k-filtering technique is required to have the complete 3D dispersion relations.

(i) The identification of the wave modes requires 4-points time series measurements of AC and DC magnetic (3D) and electric (2D) fields at frequencies up to ~200Hz to account for whistler turbulence *[~kHz sampling rate would enhance the exploration of high frequency waves]*. These measurements are required for both electron scales (100 km) and ion scales (~1000 km).

(ii) The determination of the energy partition between waves and particles requires the time series of the ion and electron moments (density and velocity) for both electron scales (100 km) and ion scales (~1000 km). Electrons should be measured with a time resolution better than 10Hz at the electron scale, at least on 2 spacecraft. *[High resolution electron measurements at 4 spacecraft would allow a full 3D characterization].* Ion distributions should be measured with 2 seconds time resolution or better at the ion scale (4 spacecraft). Higher time resolution (~ 1 Hz) ion distribution functions are required on at least one spacecraft.
.
(iii) [Because of the possible presence of very high frequency electrostatic waves, still unobserved in real plasmas but seen in recent numerical simulations, it would be useful to measure AC electric field at ~100kHz in a spacecrafts configuration at very short distance (~500m) with at least 2 s/c]

2.3.1.3 T1c Heating of particles

The heating of the particles must be measured by Cross-Scale if we want to describe the energy partition between waves and particles, and understand the dissipation mechanisms at different scales.

(i) In order to understand the phenomena responsible for the particle heating, their coupling with waves, and the way the energy is dissipated through heat, the full 3D high resolution distribution function of ions and 2D distribution functions of electrons *[and possibly heavier species, as alpha]* is required from a single spacecraft with the highest frequency possible (at least 10Hz for electrons and ~1Hz for ions). *[The same measurements performed with multi-spacecrafts at different scales (E and I) would allow to study the local effect on the particle distributions of events such as shock crossings, enhancing the understanding of the heating mechanisms.]*

(ii) The knowledge of plasma spectral properties and presence of waves is important to this point in order to link the particles heating with the cascade properties and waves. So, requirements from points T1a and T1b should be added to this issue.

2.3.2 T2 How does the magnetic field break the symmetry of plasma turbulence?

2.3.2.1 T2a Relationship between plasma conditions with the spectral anisotropies

The presence of local magnetic field means that plasma turbulence is always anisotropic, even far from boundaries or shears. Results obtained from spacecraft data in both solar wind and magnetosheath plasmas suggest that the turbulent cascades progresses differently parallel and perpendicular to the local magnetic field. The way this anisotropy develops from the injection scale to the dissipation scale and the details of the energy transfer processes are very poorly understood. Cross-Scale must provide the measurements necessary to understand the relationship between plasma conditions (magnetic field, bulk speed, presence of boundary layers and so on) with the spectral anisotropies.

(i) In order to track the development of anisotropy between scales, the determination of the 3D energy and cross-helicity wave vector spectra is required: see T1a (i) and T1a (ii).

2.3.2.2 T2b Anisotropy of distribution functions

The distribution functions of the particles are strongly anisotropic. The whole 3D distribution functions are thus needed to understand how these anisotropies develop in relation with the plasma properties. It is also important to measure the variations of the distribution functions in the 3D space, so that 4 s/c measurements would be needed. The knowledge of spectral properties of the fields and the identification of coherent structures is crucial to understand the causes of the anisotropy.

(i) Full 3D high resolution distribution function of ions and and 2D electrons *[and possibly heavier species, eg alpha, and energetic particles]* are required from 4 (ions) and at least 2 (electrons) spacecrafts at each of the different scales (with inter s/c distances in the ranges ~50 km at E-scale and ~1000 km at I-scale) to study the anisotropic evolution of the particle distributions. Sampling rate should be 2 seconds for ions at ion scales, and 10Hz for the electrons at electron scales on all spacecraft. High resolution measurements (1Hz) are also required from at least one spacecraft .

(ii) The knowledge of plasma spectral properties and presence of waves is important to this point in order to link the particles heating with the cascade properties and waves. So, requirements from point T1a should be added to this issue.

2.3.2.3 T2c Anisotropy of plasma turbulence

The anisotropy of plasma turbulence has important consequences via the formation of Kelvin-Helmotz like structures for the propagation of mass and energy through boundary layers. It is well known from numerical simulations that anisotropy strongly affects particles and field lines transport. Cross-Scale should be able to estimate these with good accuracy.

(i) To identify and characterize the structures, the AC magnetic field should be measured at all scales, with the complete 3D vision given by 4 s/c at *three ranges of scales* [see T1a (i)].

(ii) To evidence the mass transport, the ion, electron and possibly heavier particles moments are required, with the complete 3D vision given by 4 s/c at *three ranges of scales* [see T1a (ii)].

2.3.3 T3 How does the turbulent cascade form coherent structures?

2.3.3.1 T3a Identification, imaging and characterization of coherent structures

While the statistical properties of the coherent structures generated along the turbulent cascade can be studied using single-point measurements, their identification, imaging and characterization needs a full 3D view of the plasma properties. Since structures are formed along the whole cascade, 4 s/c measurements are required along all the scales involved, with more focus on the small scales of the flow where dissipation occurs. For example, the problem of intermittency in turbulence is strictly related to scale-dependent appearance of structures. Structures need to be identified to understand how energy is transported to smaller scales and eventually dissipated into heat or waves.

(i) Among the turbulent structures in solar wind, tangential or rotational discontinuities have been recently identified from one-point measurements with four with Cluster data. To better understand the origin of such structures, the way they are formed, their orientation in the space, their relationship with anisotropies, and the consequences of their presence in the flow, a 3D imaging is needed. For this, measurements of AC and DC magnetic field, and particles moments (both ions and electrons to know the total pressure) are needed from 4 s/c at [*large (~10000 km) and]* medium distance (~1000 km), with time resolution of at least ~1 sec (fields) or 2-second resolution (ion and electron distribution functions).

(ii) Shock and current sheets are also typical structures formed in solar wind turbulence. Because of their multi-scale properties, measurements of AC and DC magnetic field, as well as protons distribution functions, are required at all interesting scales [see (i)].

2.3.3.2 T3b Identification of kinetic scales structures

The kinetic scales structures are hardly identified so far. The coupling between dispersive and nonlinear effects dominates the structure formations (as for example solitons) at these ranges of scales (~1000km). It is important to measure with Cross-Scale the electromagnetic fields in order to observe, and to describe, such structures.

(i) Measurements of 3D magnetic and 2D electric AC fields are needed at high frequency (200Hz), with the 3D view given by the 4 s/c configuration, at scales ~1000 km and ~100km.

2.3.3.3 T3c Coupling between large scale structures and waves

The presence of coherent structures observed at typical large scales (discontinuities, shocks, current sheets…) could have important consequences on the small scales fields, for example through excitation of waves. Cross-Scale should be able to provide simultaneous information about the large scale structures and the small scales wave dispersion relations

(i) see point T3a (i) and (ii), and point T3b (i)

3 SCIENCE MEASUREMENT REQUIREMENT MATRIX

The accompanying spreadsheets translate the above into specific requirements and instruments (Annex 1), and a traceability matrix (Annex 2) that deploys instruments on the various spacecraft with traceable routes back to the above science requirements.

At the end of the traceability matrix a summary of the instruments required on the various spacecraft as well as the minimal configuration with 7 spacecraft are given.

4 ORBIT REQUIREMENTS

The 7 ESA spacecraft will be accommodated on a single Soyuz-Fregat 2 and launched from Kourou. JAXA will provide a separate launch for SCOPE. The apogee is of order 25 Re (up to 30 Re) and the perigee around 10 Re geocentric distance. This roughly equatorial (14 inclination) orbit enables Cross-Scale to reach the regions where the targeted physics is occurring, including the dayside bowshock (12– 22 Re), reconnection at the magnetopause (8– 12 Re) and in the “tailbox” region of the geomagnetic tail (20–30 Re), and turbulence in the solar wind (12-25 Re), magnetosheath, and geomagnetic tail/plasma sheet.

An alternative 1.4 Re x 25 Re orbit would also meet the science objectives but would need to satisfy international space debris agreements through controlled de-orbiting of all spacecraft.

4.1 Orbit for Shocks

Cross-Scale's primary location for studying collisionless shocks is at the Earth's bow shock, which is at ~14 Re at the sub-solar point flaring to ~22 Re at the dawn-dusk terminator. This full range, and tailward of the terminator, is required to efficiently study a range of field geometries and Mach numbers. The primary factors in studying the cross-scale coupling at shocks are the number of shock crossings and the speed of the crossing. This latter is dominated by the bow shock response to even small variations in solar wind pressure, resulting in motions at 10's of km/s. Multiple traversals then occur while the spacecraft are roughly in the appropriate location, and are increased by an orbit apogee that is relatively close to the bow shock, e.g. ~20 Re. Further parameter regimes will be accessible through interplanetary shocks. This requires long periods in the solar wind, facilitated by an orbit apogee > 25 Re.

4.2 Orbit for Reconnection

Cross-Scale's primary location for studying reconnection is at the Earth's magnetopause and Earth's magnetotail current sheet. Recent studies further indicate that reconnection regions also exist in the solar wind and magnetosheath. Typically, the magnetopause is at ~10 Re distance at the sub-solar point flaring to about ~15 Re at the dawn-dusk terminator. The most likely location of the near-tail reconnection is between 20 Re and 30 Re downtail, centred in the pre-midnight sector. It is required that Cross-Scale cross these reconnection regions. The primary factors in studying the cross-scale coupling are the number of current sheet crossings and the speed of the crossing. Previous observations showed that the electron-scale current sheet was traversed within ~0.1 sec, and ion-scale current sheet with a few sec. In the magnetotail current sheet, natural current sheet oscillations allow multiple crossings around the reconnection region, provided that the spacecraft is close to the neutral sheet. This requires that spacecraft have an apogee at the neutral sheet at downtail distance > 25 Re. An orbit with this apogee is expected to cover all the key reconnection regions, i.e., magnetopause, magnetotail current sheet, solar wind, and magnetosheath.

4.3 Orbit for Turbulence

Cross-Scale's primary location for studying turbulent cascade is within the solar wind, which requires an orbit apogee >= 25 Re. The low solar activity period during the years 2017-2020 will allow to observe steady and stationary fast and slow wind streams, so that turbulent cascade is not affected by local phenomena as stream interactions or high solar activity phenomena (CMEs, solar flares…). Also, the upstream region near the quasi-perpendicular bow-shock presents a great interest for the enhanced presence of waves.

The regions where turbulence anisotropy and coherent structures can be observed spans from the solar wind to the bow shock boundary layer, the magnetosheath and magnetotail. All these regions should therefore be crossed during the course of the mission.

5 SCIENCE MODE AND OPERATIONS

Operations will be centralised and, where possible, autonomous, e.g., in terms of instrument modes and data taking. The full dataset will be too large to transmit to ground. Data will be stored onboard each orbit, with a representative subset (e.g., everything except the highest resolution data from the electron scale spacecraft) telemetred to the Mission Operations Centre.

The Science Operations Centre, which could be virtual or co-located at a science data centre, will use that data to select periods of interest with regard to the science objectives of sufficient duration to fill the downlink budget. Data from those intervals, from all spacecraft, will be telemetred during the next contact period(s).

A fallback automatic selection based on average locations of the boundaries and processes and the orbital position will be in place. Onboard event selection based on suitable triggers provides an alternative and reduces the onboard storage requirements.

The operation of 7 spacecraft, and the joint operations with JAXA, to appropriately position the spacecraft in the nested, multi-scale configuration is a challenge. However, ESA has ample experience in multi-spacecraft operations from which to evolve an effective strategy. The overall configuration is relatively stable; once it has been achieved, only minimal station-keeping will be required to compensate for any small drifts. The science objectives can be met without regular adjustments to the spacecraft separations; a single reconfiguration at the end of the first year of operations is planned to fine-tune the separation strategy in the light of the initial results.

Annex 1

Science Measurement Requirements
Combined Matrix: SJS 26 March 2008 + Updates CPE 7 April 2008
Items in italics are desirable if resources permit
 # = number of spacecraft on which measurement needs to be made

Req.	Measurement	electron #	electron sep (km)	electron dt (s)	ion #	ion sep (km)	ion dt (s)	*fluid #*	*fluid sep (km)*	*fluid dt (s)*	Instr	
S1	How do shocks accelerate particles?											
S1A	**Shock parameters**											
S1a(i)	dc B	4	100	0.01	4	1000	0.5	*4*	*>10,000*	*1*	MAG	
S1a(ii)	np, vp, Tp, Tperp/Tpara				>=2	>=1000	spin	*2*	*>5000*	*spin*	IESA (alt CESA)	
S1a(ii)	ne, Te				>=2	>=1000	spin	*2*	*>5000*	*spin*	EESA (alt CESA)	
S1B	**Measure accelerated particles**											
S1b(i)	proton f(v) < 30keV				4	1000	<=2	*2*	*>5000*	*spin*	IESA (alt CESA)	
S1b(i)	electron f(v) < 30keV	>=1	100	0.1	1	1000	<=2				EESA (alt CESA?)	
S1b(ii)	alpha, CNO f(v) < 40keV				>=1	1000	60				ICA	
S1b(iii)	p,e f(v) 30-100's keV	1		spin	>=1	1000	spin	*>=1*	*>5000*	*spin*	HEP	
S1C	**Acceleration agents: electric fields**											
S1c(i)	dc B	4	<100	0.01							MAG	
S1c(i)	dc E 3D	1		0.01							2x inclined E2D (or E3D)	
S1c(i)	dc E 2D	4	100	0.01							E2D	
S1c(ii)	ac B	4	100	0.01	2	>=1000	0.1				ACB	
S1c(ii)	ac E 2D	4	100	0.01	2	>=1000	0.1				E2D	
S2	How is the energy incident on a shock partitioned?											
S2A	**Measure energised particles**											
S2a(i)	proton f(v) < 30keV				4	1000	<=2				IESA (alt CESA)	
S2a(ii)	electron f(v) < 30keV	>=2	100	0.1							EESA (alt CESA)	
S2a(iii)	alpha, CNO f(v) < 40keV				1		60				ICA	
S2B	**Shock transition layer and waves**											
S2b(i)	dc B 3D	4	<100	0.01	4	1000	0.1				MAG	
S2b(i)	dc E 3D	1		0.01							2x inclined E2D (or E3D)	
S2b(i)	dc E 2D	4	100	0.01	4	1000	0.1				E2D	
S2b(ii)	ac B 3D	4	100	0.2 ms	4	1000	0.1				ACB	
S2b(ii)	ac E 2D	4	100	0.2 ms	4	1000	0.1				E2D	
S3	How do shock variability and reformation influence shock acceleration?											
S3A	**Reveal shock variability and reformation properties**											
S3a(i)	dc B	4	100	0.01	4	1000	0.1	*4*	*>10,000*	*1*	MAG	
S3a(i)	dc E 3D	1		0.01							2x inclined E2D (or E3D)	
S3a(i)	dc E 2D	4	100	0.01	4	1000	0.1				E2D	
S3a(ii)	proton f(v) < 30keV				4	1000	<=2				IESA (alt CESA)	
S3a(iii)	ac B 3D	4	100	0.2 ms	4	>=1000	0.2 ms				ACB	
S3a(iii)	ac E 2D	4	100	0.2 ms	4	>=1000	0.2 ms				E2D	
S3a(iv)	electron f(v) < 30keV	>=2	100	0.1							EESA	
R1	What initiates magnetic reconnection ?											
A:Follow current sheet thinning												
R1a(i)	dc B	4	5-50	0.02	4	100 -500	0.02	*4*	*5000-15000*	*spin*	MAG	
R1a(ii)	np, vp, Tp				>=2	100-500	2	>=2	*5000-15000*	*spin*	IESA	
R1a(ii)	ne, Te, Ve				>=2	100-500	2				SCOPE + EESA	
B:Identify reconnection onset												
R1b(i)	dc B	4	5-50	0.02	4	100-500	0.02				MAG	
R1b(i)	*dc E 3D*	*1*									SCOPE	
R1b(i)	dc E 2D	>=2	5-50	0.02	>=2	100-500	0.02				E2D	
R1b(ii)	ac B	4	5-50	1 ms	4	100-500	0.02				ACB	
R1b(ii)	ac E 2D	>=2	5-50	0.01ms	>=2	100-500	0.02				E2D	
R1b(ii)	*ac E 3D*	*1*		0.01ms							SCOPE	
R1b(iii)	proton f(v) < 30keV				>=2	100 - 500	2	>=2	*5000-15000*	*spin*	SCOPE + IESA	
R1b(iv)	electron f(v) < 30keV	>=1		0.02							SCOPE	
R1b(iv)	*electron f(v) < 30keV*	>=2	*5-50*	*0.1*	*>=2*	*100 - 500*	*0.1*				*SCOPE + EESA*	
C: Determine external/enviromental condition												
R1c(i)	dc B							*4*	*5000-15000*	*spin*	MAG	
R1c(i)	np, vp, Tp							*4*	*5000-15000*	*spin*	IESA	
R1c(ii)	*alpha, CNO f(v) < 40keV*				**1*		*spin*				*OK at any scale	
R2	How does the magnetic topology evolve ?											
A: Topology changes												
R2a(i)	dc B	4	5-50	0.02							MAG	
R2a(i)	dc E 3D	1		0.02							E3D	or SCOPE
R2a(ii),(ii	dc B				>=2	100 - 500	0.02	>=2	*5000-15000*	*spin*	MAG	
R2a(ii),(ii	dc E 2D				>=2	100 - 500	0.02	>=2	*5000-15000*	*spin*	E2D	
B: Identify regions												
R2b(i)	dc B	>=1	5-50	0.02							MAG	
R2b(i)	dc E 3D	>=1	5-50	0.02							E3D	
R2b(i)	electron f(v) < 30keV	>=1	5-50	0.02							EESA	or SCOPE
R2b(ii)	dc B				4	100 - 500	1				MAG	
R2b(ii)	dc E 2D				>=1	100 - 500	1				E2D	
R2b(ii)	electron f(v) < 30keV				>=1	100 - 500	1				CESA	or SCOPE + EESA
R2b(ii)	proton f(v) < 30keV				>=1	100 - 500	1	*>=1*	*5000-15000*	*spin*	CESA	or SCOPE + IESA
R2b(iii)	electron f(v) < 30keV	>=1	5-50	0.02							EESA	or SCOPE
R2b(iii)	ac B	>=1	5-50	1 ms							ACB	
R2b(iii)	ac E 2D	>=1	5-50	0.01ms							E2D	
R2b(iv)	electron f(v) < 30keV	>=2	5-50	0.02							EESA	or SCOPE
R2b(iv)	*electron f(v) < 30keV*				*>=2*	*100 - 500*	*1*				*CESA*	*or SCOPE + EESA*
C: Determine external/enviromental conditions												
R2c(i)	dc B							*4*	*5000-15000*	*spin*	MAG	
R2c(ii)	dc B							*4*	*5000-15000*	*spin*	MAG	
R2c(ii)	np, vp, Tp							*4*	*5000-15000*	*spin*	IESA or CESA	
R2c(iii)	*alpha, CNO f(v) < 40keV*				*≥*1*		*spin*				*1sc at any scale	ICA or SCOPE
D:Reconnection in Turbulent Plasmas												

R2d(i)	electron f(v) < 30keV	>=2	5-50	0.02							EESA	or SCOPE
R2d(i)	electron f(v) < 30keV				>=2	100 - 500	1				CESA	or SCOPE + EESA
R2d(i)	proton f(v) < 30keV				>=2	100 - 500	1	>=2	5000-15000	spin	CESA	or SCOPE + IESA
R2d(ii)	dc B				4	100 - 500	1	4	5000-15000	spin	MAG	
R3	How does reconnection accelerate particles and heat plasma?											
A:Geometry and boundary conditions												
R3a(i)	dc B	4	5-50	0.01	4	100 - 500	0.02	4	5000-15000	spin	MAG, ACB	
R3a(i)	n (s/c pot.)	4	5-50	0.01	4	100 - 500	0.02	4	5000-15000	spin	E2D	
R3a(ii)	dc B				>=2	100 - 500	2	>=2	5000-15000	spin	MAG	
R3a(ii)	proton f(v) < 30keV				>=2	100 - 500	2	>=2	5000-15000	spin	IESA	
R3a(ii)	electronf(v) < 30keV				>=2	100 - 500	2				EESA	
B:Accelerated particles												
R3b(i)	proton f(v) < 30keV				>=2	100 - 500	2	>=2	5000-15000	spin	IESA	
R3b(i)	electron f(v) < 30keV	1		0.02							SCOPE	
R3b(i)	electron f(v) < 30keV	>=2	5-50	2	>=2	100 - 500	2				SCOPE + EESA	
R3b(ii)	alpha, CNO f(v) < 40 keV				*1		spin				*OK at any scale	SCOPE
R3b(iii)	proton f(v) < 1MeV				1	100 - 500	spin	>=2	5000-15000	spin	HEP	
R3b(iii)	electron f(v) < 200keV				>=1	100 - 500	spin				HEP	
C:Electromagnetic fields												
R3c(i)	dc B	4	5-50	0.01	4	100 - 500	0.02				MAG	
R3c(i)	dc E 2D	>2	5-50	0.01	>2	100 - 500	0.02				E2D	
R3c(i)	dc E 3D	1		0.01							SCOPE or 2 s/c E2D	
R3c(ii)	ac B	4	5-50	1 ms	4	100 - 500	1 ms	1		1 ms	ACB	
R3c(ii)	ac E 2D	>2	5-50	0.01ms	>2	100 - 500	0.01ms	1		0.01ms	E2D	
R3c(ii)	ac E 3D	1		0.01ms							SCOPE or 2s/c E2D	
T1 - TURBULENT CASCADE												
T1a - cascade												
T1a(i)	dc B	4	100	0.05	4	1000	0.05	4	>10,000	0.05	MAG	
T1a(i)	ac B	4	100	0.002	4	1000	0.002	4	>10,000	0.002	ACB	
T1a(i)	ac + dc E 2D	4	100	0.002	4	1000	0.002				E2D	
T1a(ii)	proton f(v) < 30keV				>=1	1000	1	4	>10000	spin	IESA (alt CESA)	
T1a(ii)	proton f(v) < 30keV				3	1000	2				IESA (alt CESA)	
T1a(ii)	electron f(v) < 30keV	>=2	100	0.1	4	1000	2				EESA (alt CESA)	
T1a(iii)	timing-position accuracy..											
T1b - waves												
T1b(i)	dc B	4	100	0.05	4	1000	0.05				MAG	
T1b(i)	ac B	4	100	0.002	4	1000	0.002				ACB	
T1b(i)	ac + dc E 2D	4	100	0.002	4	1000	0.002				E2D	
T1b(ii)	proton f(v) < 30keV				>=1	1000	1	4	>10000	spin	IESA (alt CESA)	
T1b(ii)	electron f(v) < 30keV	>=2	100	0.1	4	1000	2				EESA (alt CESA)	
T1b(ii)	proton f(v) < 30keV				3	1000	2				IESA (alt CESA)	
T1b(iii)	ac + dc E 2D	>=2	0.5	1.00E-05							E2D	
T1c - heating												
T1c(i)	proton f(v) < 30keV				>=1	1000	1	4	>5000	spin	IESA (alt CESA)	
T1c(i)	2D electron f(v) < 30keV	>=1	100	0.1	>=1	1000	2				EESA (alt CESA?)	
T1c(i)	alpha, CNO f(v) < 40keV				2	1000	1				ICA	
T1c(i)	p,e f(v) 30-100's keV	1	100	0.1	1	1000	1	1	>5000	spin	HEP	
T1c(ii)	dc B	4	100	0.05	4	1000	0.05	4	>10,000	0.05	MAG	
T1c(ii)	ac B	4	100	0.002	4	1000	0.002	4	>10,000	0.002	ACB	
T2 - ANISOTROPY												
T2a - cascade anisotropy												
T2a(i)	dc B	4	100	0.05	4	1000	0.05	4	>10,000	0.05	MAG	
T2a(i)	ac B	4	100	0.002	4	1000	0.002	4	>10,000	0.002	ACB	
T2a(i)	proton f(v) < 30keV				>=1	1000	1	1	>10000	spin	IESA (alt CESA)	
T2a(i)	2D electron f(v) < 30keV	>=2	100	0.1	4	1000	2	1	>10000	spin	EESA (alt CESA)	
T2a(i)	proton f(v) < 30keV				3	1000	2				IESA (alt CESA)	
T2a(i)	ne, ve	4	100	0.1				1	>10000	spin	EESA (alt CESA)	
T2b - particle anisotropy												
T2b(i)	proton f(v) < 30keV				>=1	1000	1	1	>10000	spin	IESA (alt CESA)	
T2b(i)	2D electron f(v) < 30keV	>=2	100	0.1	4	1000	2	1	>10000	spin	EESA (alt CESA)	
T2b(i)	proton f(v) < 30keV				3	1000	2				IESA (alt CESA)	
T2b(i)	alpha, CNO f(v) < 40keV	1		4	1	1000	1				ICA	
T2b(i)	p,e f(v) 30-100's keV	1		4	>=1	1000	1	1	>5000	spin	HEP	
T2b(ii)	dc B	4	100	0.05	4	1000	0.05	4	>10,000	0.05	MAG	
T2b(ii)	ac B	4	100	0.002	4	1000	0.002	4	>10,000	0.002	ACB	
T2c - transport												
T2c(i)	dc B	4	100	0.05	4	1000	0.05	4	>10,000	0.05	MAG	
T2c(i)	ac B	4	100	0.002	4	1000	0.002	4	>10,000	0.002	ACB	
T2c(ii)	proton f(v) < 30keV				>=1	1000	1	1	>10000	spin	IESA (alt CESA)	
T2c(ii)	2D electron f(v) < 30keV	>=2	100	0.1	4	1000	2	1	>10000	spin	EESA (alt CESA)	
T2c(ii)	proton f(v) < 30keV				3	1000	2				IESA (alt CESA)	
T2c(ii)	ne, ve	4	100	0.1	4	1000	1	1	>10000	spin	EESA (alt CESA)	
T3 - STRUCTURES												
T3a - imaging: large scale												
T3a(i)	dc B				4	1000	0.1	4	>10000	0.1	MAG	
T3a(i)	ac B				4	1000	0.02	4	>10000	0.02	ACB	
T3a(i)	proton f(v) < 30keV				4	1000	2	1	>10000	spin	IESA (alt CESA)	
T3a(i)	electron f(v) < 30keV				1	1000	2	1	>10000	spin	EESA (alt CESA)	
T3a(ii)	dc B				4	1000	0.1	4	>10000	0.1	MAG	
T3a(ii)	ac B				4	1000	0.02	4	>10000	0.02	ACB	
T3a(ii)	proton f(v) < 30keV				4	1000	2	1	>10000	spin	IESA (alt CESA)	
T3a(ii)	electron f(v) < 30keV				1	1000	2	1	>10000	spin	EESA (alt CESA)	
T3b - solitons: small scales												
T3b(i)	dc B	4	100	0.05	4	1000	0.05				MAG	
T3b(i)	ac B	4	100	0.002	4	1000	0.002				ACB	
T3b(i)	ac + dc E 2D	4	100	0.002	4	1000	0.002				E2D	

T3c - coupling structures/waves												
T3c(i)	dc B	4	100	0.05	4	1000	0.05	*4*	*>10000*	*0.1*	MAG	
T3c(i)	ac B	4	100	0.002	4	1000	0.002	*4*	*>10000*	*0.02*	ACB	
T3c(i)	proton f(v) < 30keV				4	1000	*2*	*1*	*>10000*	*spin*	IESA (alt CESA)	
T3c(i)	electron f(v) < 30keV				1	1000	*2*	*1*	*>10000*	*spin*	EESA (alt CESA)	

Annex 2

Cross-Scale Science Measurement Requirements
Combined Matrix: SJS 26 March 2008 + Updates CPE 7 April 2008
Items in italics are desirable if resources permit
CPP wherever there are particle instruments
** = assuming 15 rpm spin-rate*
Firm Requirement
Highly Desirable Requirement
Some further iteration with science requirements is still possible should spacecraft resources demand it.
 # = number of sensors/locations on s/c

Inst	e1	#	e2	#	e3	#	e4	#	i1	#	i2	#	i3	#	i4	#	*f1*	#	*f2*	#	*f3*	#	*f4*	#
ACB	R1b(ii)	1	R1b(ii)	1	R1b(ii)	1	R1b(ii)	1	R1b(ii)	1	R1b(ii)	1	R1b(ii)	1	R1b(ii)	1								
ACB	R2b(iii)	1																						
ACB	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1																
ACB	R3c(ii)	1	R3c(ii)	1	R3c(ii)	1	R3c(ii)	1	R3c(ii)	1	R3c(ii)	1	R3c(ii)	1	R3c(ii)	1	*R3c(ii)*	1						
ACB	S1c(ii)	1	S1c(ii)	1	S1c(ii)	1	S1c(ii)	1	S1c(ii)	1	S1c(ii)	1												
ACB	S2b(ii)	1	S2b(ii)	1	S2b(ii)	1	S2b(ii)	1	S2b(ii)	1	S2b(ii)	1	S2b(ii)	1	S2b(ii)	1								
ACB	S3a(iii)		S3a(iii)	1	S3a(iii)	1	S3a(iii)	1	S3a(iii)	1	S3a(iii)	1	S3a(iii)	1	S3a(iii)	1								
ACB	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	*T1a(i)*	*1*	*T1a(i)*	*1*	*T1a(i)*	*1*	*T1a(i)*	*1*
ACB	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1								*1*
ACB	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	*T1c(ii)*	*1*	*T1c(ii)*	*1*	*T1c(ii)*	*1*	*T1c(ii)*	*1*
ACB	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	*T2a(i)*	*1*	*T2a(i)*	*1*	*T2a(i)*	*1*	*T2a(i)*	*1*
ACB	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	*T2b(ii)*	*1*	*T2b(ii)*	*1*	*T2b(ii)*	*1*	*T2b(ii)*	*1*
ACB	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	*T2c(i)*	*1*	*T2c(i)*	*1*	*T2c(i)*	*1*	*T2c(i)*	*1*
ACB									T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1	*T3a(i)*	*1*	*T3a(i)*	*1*	*T3a(i)*	*1*	*T3a(i)*	*1*
ACB									T3a(ii)	1	T3a(ii)	1	T3a(ii)	1	T3a(ii)	1	*T3a(i)*	*1*	*T3a(i)*	*1*	*T3a(i)*	*1*	*T3a(i)*	*1*
ACB	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1								*1*
ACB	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	*T3c(i)*	*1*	*T3c(i)*	*1*	*T3c(i)*	*1*	*T3c(i)*	*1*
ACDPU	?		?		?		?		?		?		?		?		?		?		?		?	
ACDPU	?		?		?		?		?		?		?		?		?		?		?		?	
ACDPU		1		1		1		1		1		1		1		1		1		1		1		1
ACDPU	?		?		?		?		?		?		?		?		?		?		?		?	
ASP	S2a(ii)	1	S2a(ii)	1					*S1a(ii)*	*1*														
ASP	T1a(ii)	1							*T1a(ii)*	*1*														
ASP	T2a(ii)	1							*T2a(ii)*	*1*														
ASP	T3a(ii)	1							*T3a(ii)*	*1*														
CPP	*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*	
CPP	*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*	
CPP		*1*								*1*		*1*		*?*		*?*		*1*		*1*		*?*		*?*
CPP	*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*		*?*	
E2D	R1b(i)	4	R1b(i)	4					R1b(i)	4	R1b(i)	4												
E2D	R1b(ii)	4	R1b(ii)	4					R1b(ii)	4	R1b(ii)	4												
E2D									R2a(ii)	4	R2a(ii)	4					*R2a(ii)*	*4*	*R2a(ii)*	*4*				
E2D									R2b(ii)	4	R2b(ii)	4												
E2D	R2b(iii)	4																						
E2D	R3a(i)	4	R3a(i)	4	R3a(i)	4	R3a(i)	4	R3a(i)	4	R3a(i)	4	R3a(i)	4	R3a(i)	4	*R3a(i)*	*4*	*R3a(i)*	*4*	*R3a(i)*	*4*	*R3a(i)*	*4*
E2D	R3c(i)	4	R3c(i)	4	R3c(i)	4			R3c(i)	4	R3c(i)	4	R3c(i)	4										
E2D	R3c(ii)	4	R3c(ii)	4	R3c(ii)	4			R3c(ii)	4	R3c(ii)	4	R3c(ii)	4			*R3c(ii)*	*4*						
E2D	S1c(i)	4	S1c(i)	4	S1c(i)	4	S1c(i)	4																
E2D	S1c(ii)	4	S1c(ii)	4	S1c(ii)	4	S1c(ii)	4	S1c(ii)	4	S1c(ii)	4												
E2D	S2b(i)	4	S2b(i)	4	S2b(i)	4	S2b(i)	4	S2b(i)	4	S2b(i)	4	S2b(i)	4	S2b(i)	4								
E2D	S2b(ii)	4	S2b(ii)	4	S2b(ii)	4	S2b(ii)	4	S2b(ii)	4	S2b(ii)	4	S2b(ii)	4	S2b(ii)	4								
E2D	S3a(i)	4	S3a(i)	4	S3a(i)	4	S3a(i)	4	S3a(i)	4	S3a(i)	4	S3a(i)	4	S3a(i)	4								
E2D	S3a(iii)	4	S3a(iii)	4	S3a(iii)	4	S3a(iii)	4	S3a(iii)	4	S3a(iii)	4	S3a(iii)	4	S3a(iii)	4								
E2D	T1a(i)	4	T1a(i)	4	T1a(i)	4	T1a(i)	4	T1a(i)	4	T1a(i)	4	T1a(i)	4	T1a(i)	4								
E2D	T1b(i)	4	T1b(i)	4	T1b(i)	4	T1b(i)	4	T1b(i)	4	T1b(i)	4	T1b(i)	4	T1b(i)	4								
E2D	T3b(i)	4	T3b(i)	4	T3b(i)	4	T3b(i)	4	T3b(i)	4	T3b(i)	4	T3b(i)	4	T3b(i)	4								
E2D (incl)	*R1b(i)*	*4*																						
E2D (incl)	*R1b(ii)*	*4*																						
E2D (incl)	R2a(i)	4																						
E2D (incl)	R2b(i)	4																						
E2D (incl)	R3c(i)	4																						
E2D (incl)	R3c(ii)	4																						
E2D (incl)	S1c(i)	4			S1c(i)	4																		
E2D (incl)	S1c(ii)	4			S1c(ii)	4																		
E2D (incl)	S2b(i)	4			S2b(ii)	4																		
E2D (incl)	S2b(ii)	4			S2b(ii)	4																		
E2D (incl)	S3a(i)	4			S3a(i)	4																		
E3D	*R1b(i)*	*2*																						
E3D	*R1b(ii)*	*2*																						
E3D	R2a(i)	2																						
E3D	R2b(i)	2																						
E3D	R3c(i)	2																						
E3D	R3c(ii)	2																						
E3D	S1c(i)	2																						
E3D	S1c(ii)	2																						
E3D	S2b(i)	2																						
E3D	S2b(ii)	2																						
E3D	S3a(i)	2																						
EESA									R1a(ii)	2	R1a(ii)	2												
EESA	R1b(iv)	4	*R1b(iv)*	*4*					*R1b(iv)*	*4*	*R1b(iv)*	*4*												
EESA	R2b(i)	4	*R2b(i)*	*4*																				
EESA									R2b(ii)	2														
EESA	R2b(iii)	4																						
EESA	R2b(iv)	4	R2b(iv)	4					*R2b(iv)*	*2*	*R2b(iv)*	*2*												

EESA	R2d(i)	4	R2d(i)	2					R2d(i)	2	R2d(i)	2												
EESA									R3a(ii)	2	R3a(ii)	2												
EESA	R3b(i)	4	R3b(i)	1					R3b(i)	1	R3b(i)	1												
EESA									S1a(ii)	1	S1a(ii)	1					S1a(ii)	1	S1a(ii)	1				
EESA	S1b(i)	4	S1b(i)	4					S1b(i)	2*														
EESA	S2a(ii)	4	S2a(ii)	4																				
EESA	S3a(iv)	4	S3a(iv)	4																				
EESA	T1a(ii)	4	T1a(ii)	4					T1a(ii)	2	T1a(ii)	2	T1a(ii)	2	T1a(ii)	2	T1a(ii)	1	T1a(ii)	1	T1a(ii)	1	T1a(ii)	1
EESA	T1b(ii)	4	T1b(ii)	4					T1b(ii)	2	T1b(ii)	2	T1b(ii)	2	T1b(ii)	2								
EESA	T1c(i)	4	T1c(i)	4					T1c(i)	2	T1c(i)	1	T1c(i)	1	T1c(i)	1								
EESA	T2a(i)	4	T2a(i)	4					T2a(i)	2	T2a(i)	2	T2a(i)	2	T2a(i)	2								
EESA	T2a(i)	4	T2a(i)	4	T2a(i)	4	T2a(i)	4									T2a(i)	1						
EESA	T2b(i)	4	T2b(i)	4					T2b(i)	2	T2b(i)	2	T2b(i)	2	T2b(i)	2	T2b(i)	1						
EESA	T2c(ii)	4	T2c(ii)	4					T2c(ii)	2	T2c(ii)	2	T2c(ii)	2	T2c(ii)	2	T2c(ii)	1	T2c(ii)	1	T2c(ii)	1	T2c(ii)	1
EESA	T2c(ii)	4	T2c(ii)	4					T2c(ii)	4	T2c(ii)	4	T2c(ii)	4	T2c(ii)	4	T2c(ii)	1						
EESA									T3a(i)	2							T3a(i)	1						
EESA									T3a(ii)	2							T3a(ii)	1						
EESA									T3c(i)	2							T3c(i)	1						
HEP													R3b(ii)	1			R3b(ii)		R3b(ii)					
HEP											R3b(iii)	1	R3b(iii)	1										
HEP							S1b(iii)	1	S1b(iii)	1?			S1b(iii)	1	S1b(iii)	1?	S1b(iii)	1	S1b(iii)	1	S1b(iii)	1	S1b(iii)	1
HEP							T1c(i)	2					T1c(i)	2			T1c(i)	2						
HEP							T2b(i)	2					T2c(i)	2			T2b(i)	2						
ICA															*R2c(iii)	1								
ICA															R1c(ii)	1								
ICA															R3b(ii)	1								
ICA															S1b(ii)	1								
ICA															S2a(iii)	1								
ICA											T1c(i)	2			T1c(i)	2								
ICA											T2b(i)	2			T2b(i)	2								
IESA									R1a(ii)	2	R1a(ii)	2					R1a(ii)	1	R1a(ii)	1				
IESA									R1b(iii)	2	R1b(iii)	2					R1b(iii)	1	R1b(iii)	1				
IESA																	R1c(i)	1	R1c(i)	1	R1c(i)	1	R1c(i)	1
IESA									R2b(ii)	2							R2b(ii)	1						
IESA																	R2c(ii)	1	R2c(ii)	1	R2c(ii)	1	R2c(ii)	1
IESA									R2d(i)	2	R2d(i)	2					R2d(i)	1	R2d(i)	1				
IESA									R3a(ii)	2	R3a(ii)	2					R3a(ii)	1	R3a(ii)	1				
IESA									R3b(i)	1	R3b(i)	1					R3b(i)	1	R3b(i)	1				
IESA									S1a(ii)	1	S1a(ii)	1					S1a(ii)	1	S1a(ii)	1				
IESA									S1b(i)	2*	S1b(i)	2*	S1b(i)	2*	S1b(i)	2*	S1b(i)	1	S1b(i)	1				
IESA									S2a(i)	2*	S2a(i)	2*	S2a(i)	2*	S2a(i)	2								
IESA									S3a(ii)	2*	S3a(ii)	2*	S3a(ii)	2*	S3a(ii)	2								
IESA									T1a(ii)	2	T1a(ii)	4*	T1a(ii)	2	T1a(ii)	2	T1a(ii)	1	T1a(ii)	1	T1a(ii)	1	T1a(ii)	1
IESA									T1b(ii)	2	T1b(ii)	4*	T1b(ii)	2	T1b(ii)	2	T1b(ii)	1	T1b(ii)	1	T1b(ii)	1	T1b(ii)	1
IESA									T1c(i)	4	T1c(i)	4*	T1c(i)	4	T1c(i)	4	T1c(i)	1	T1c(i)	1	T1c(i)	1	T1c(i)	1
IESA									T2a(ii)	1	T2a(ii)	4*	T2a(ii)	1	T2a(ii)	1	T2a(ii)	1						
IESA									T2b(i)	1	T2b(i)	4*	T2b(i)	1	T2b(i)	1	T2b(i)	1						
IESA									T2c(ii)	1	T2c(ii)	4*	T2c(ii)	1	T2c(ii)	1	T2c(ii)	1						
IESA									T3a(i)	2	T3a(i)	2	T3a(i)	2	T3a(i)	2	T3a(i)	1						
IESA									T3a(ii)	2	T3a(ii)	2	T3a(ii)	2	T3a(ii)	2	T3a(i)	1						
IESA									T3c(i)	2	T3c(i)	2	T3c(i)	2	T3c(i)	2	T3c(i)	1						
MAG	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1	R1a(i)	1
MAG	R1b(i)	1	R1b(i)	1	R1b(i)	1	R1b(i)	1	R1b(i)	1	R1b(i)	1	R1b(i)	1	R1b(i)	1								
MAG																	R1c(i)	1	R1c(i)	1	R1c(i)	1	R1c(i)	1
MAG	R2a(i)	1	R2a(i)	1	R2a(i)	1	R2a(i)	1																
MAG									R2a(ii)	1	R2a(ii)	1					R2a(ii)	1	R2a(ii)	1				
MAG	R2b(i)	1																						
MAG									R2b(ii)	1	R2b(ii)	1	R2b(ii)	1	R2b(ii)	1								
MAG									R2d(ii)	1	R2d(ii)	1	R2d(ii)	1	R2d(ii)	1	R2d(ii)	1	R2d(ii)	1	R2d(ii)	1	R2d(ii)	1
MAG																	R2c(i)	1	R2c(i)	1	R2c(i)	1	R2c(i)	1
																	R2c(ii)	1	R2c(ii)	1	R2c(ii)	1	R2c(ii)	1
MAG	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1	R3a(i)	1
MAG									R3a(ii)	1	R3a(ii)	1					R3a(ii)	1	R3a(ii)	1				
MAG	R3c(i)	1	R3c(i)	1	R3c(i)	1	R3c(i)	1	R3c(i)	1	R3c(i)	1	R3c(i)	1	R3c(i)	1								
MAG	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1	S1a(i)	1
MAG	S1c(i)	1	S1c(i)	1	S1c(i)	1	S1c(i)	1																
MAG	S2b(i)	1	S2b(i)	1	S2b(i)	1	S2b(i)	1	S2b(i)	1	S2b(i)	1	S2b(i)	1	S2b(i)	1								
MAG	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1	S3a(i)	1
MAG	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1	T1a(i)	1
MAG	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1	T1b(i)	1								1
MAG	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1	T1c(ii)	1
MAG	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1	T2a(i)	1
MAG	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1	T2b(ii)	1
MAG	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1	T2c(i)	1
MAG									T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1
MAG									T3a(ii)	1	T3a(ii)	1	T3a(ii)	1	T3a(ii)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1	T3a(i)	1
MAG	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1	T3b(i)	1								1
MAG	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1	T3c(i)	1

Summary Requirements

Inst	e1	#	e2	#	e3	#	e4	#	i1	#	i2	#	i3	#	i4	#	f1	#	f2	#	f3	#	f4	#
	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1	ACB	1
	ASP	1	ASP	1																				
	E2D	4	E2D	4	E2D	4	E2D	4	E2D	4	E2D	4	E2D	4	E2D	4								
	E2Dincl	4			E2Dincl	4																		
(scope only)	E3D	2																						

	EESA	4	EESA	4					EESA	2	EESA	2	EESA	2	EESA	2								
							HEP	1					HEP	1			*HEP*	*1*	*HEP*	*1*				
(or scope)															ICA	1								
									IESA	2	IESA	4	IESA	2	IESA	2	*IESA*	*1*	*IESA*	*1*	*IESA*	*1*	*IESA*	*1*
	MAG	1	MAG	1	MAG	1	MAG	1	MAG	1	MAG	1	MAG	1	MAG	1	*MAG*	*1*	*MAG*	*1*	*MAG*	*1*	*MAG*	*1*
	ACDPU	1	ACDPU	1	ACDPU	1	ACDPU	1	ACDPU	1	ACDPU	1	ACDPU	1	ACDPU	1	*ACDPU*	*1*	*ACDPU*	*1*	*ACDPU*	*1*	*ACDPU*	*1*
	CPP	1	CPP	1			CPP	1	CPP	1	CPP	1	CPP	1	CPP	1	*CPP*	*1*	*CPP*	*1*	*CPP*	*1*	*CPP*	*1*

7 Spacecraft Minimal configuration

	1 or scope		2		3 or scope				4		5		6		7									
Inst	e1	#	e2	#	e3	#			i1/e4	#	i2	#	i3	#	i4	#	*f1*	*#*	*f2*	*#*	*f3*	*#*	*f4*	*#*
	ACB	1	ACB	1	ACB	1			ACB	1	ACB	1	ACB	1	ACB	1	*ACB*	*1*	*ACB*	*1*	*ACB*	*1*	*ACB*	*1*
	ASP	1	ASP	1																				
	E2D	4	E2D	4	E2D	4			E2D	4	E2D	4	E2D	4	E2D	4								
	E2Dincl	4			E2Dincl	4																		
(scope only)	E3D	2																						
	EESA	4	EESA	4					EESA	2	EESA	2	EESA	2	EESA	2								
									HEP	1			HEP	1			*HEP*	*1*	*HEP*	*1*				
(or scope)															ICA	1								
									IESA	2	IESA	4	IESA	2	IESA	2	*IESA*	*1*	*IESA*	*1*	*IESA*	*1*	*IESA*	*1*
	MAG	1	MAG	1	MAG	1			MAG	1	MAG	1	MAG	1	MAG	1	*MAG*	*1*	*MAG*	*1*	*MAG*	*1*	*MAG*	*1*
	ACDPU	1	ACDPU	1	ACDPU	1			ACDPU	1	ACDPU	1	ACDPU	1	ACDPU	1	*ACDPU*	*1*	*ACDPU*	*1*	*ACDPU*	*1*	*ACDPU*	*1*
	CPP	1	CPP	1					CPP	1	CPP	1	CPP	1	CPP	1	*CPP*	*1*	*CPP*	*1*	*CPP*	*1*	*CPP*	*1*