Low frequency electric field and density fluctutation measurements on Solar Orbiter

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Abstract

Solar Orbiter will orbit the Sun down to 0.2 AU distance allowing detailed in-situ studies of important but unexplored regions of the solar wind in combination with coordinated remote sensing of the Sun. In-situ measurements require high quality measurements of particle distributions and electric and magnetic fields. We show that such important scientific topics as identification of coronal heating remnants, solar wind turbulence, magnetic reconnection and shock formation within coronal mass ejections all require electric field and plasma density measurements in the frequency range from DC up to about 1000 Hz. We discuss how such measurements can be achieved using double-probe technique. We sketch a few possible antenna design solutions.

Key words: electric field, Solar Orbiter, solar wind

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1 Introduction

Solar Orbiter is an ESA mission planned for launch after 2015 that is going to produce images of the Sun at an unprecedented resolution and perform the closest ever in-situ measurements. The Solar Orbiter will have a 150-day orbit with the perihelion at $0.22\,\mathrm{AU}{\sim}47\,\mathrm{R}_{\odot} \sim 33 \times 10^{6}\,\mathrm{m}$. At perihelion the orbital differential motion relative to the Sun becomes as low as 2.5°/day allowing investigations of the temporal evolution of solar phenomena both remotely and in situ. The orbit is in 3:2 resonance with Venus and the inclination of the orbit is increased at each Venus passage, and at the end of the nominal mission the inclination will exceed 30°. Thus, the Solar Orbiter will cover a wide range of latitudes allowing studies of different solar phenomena.

The Solar Orbiter is planned to have two suites of instruments, one for remote observations of the Sun and another for *in situ* observations. The *in situ* instruments can be divided in two big packages: the Field Package and the Particle Package. By coming closer to the Sun than any other earlier spacecraft the Solar Orbiter will be able to make very high resolution remote observations of the Sun which in combination with in situ measurements, which have never been made so close to the Sun, should give a lot of new scientific results on the Sun and the solar atmosphere.

When choosing particular instruments for the mission different compromises must be made regarding the design, the measurement range, the resolution, the quality, etc. All these compromises and trade-offs are weighted one against the other based on the scientific objectives, constraints of power, mass, design,

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etc. In the case of the Fields Package the major compromises are related to the number, type, design and location of antennas. Here we argue that there are many important science questions where significant closure could be achieved when the Fields Package can supply measurements of low frequency electric field and density fluctuations. By low frequency we here mean DC up to ∼1000 Hz thus covering MHD scales and frequencies up to characteristic ion and ion/electron scales. This also puts some significant constraints on the possible antenna design.

In the Science section we discuss a few examples of important science questions that require low frequency electric field and density fluctuation measurements. In the Context session we discuss the available low frequency electric field and density measurements from other spacecraft missions in past as well as upcoming missions. Particularly we stress what would be the advantages to carry out such measurements by the Solar Orbiter. In the Instrumentation section we give suggestions for a few possible technical solutions and discuss their advantages and disadvantages. The results are summarized in the Conclusion section.

2 Science

One of the top-level scientific goals of the Solar Orbiter mission is to "Determine the properties, dynamics and interactions of plasma, fields and particles in the near-Sun heliosphere" (Solar Orbiter. Science Requirements Document. 31 March 2005). Under this top level goal there are many more specific questions, some examples of which we will address below. However, one can note directly some general things about using electric field E and density fluctuations δn measurements.

- The availability of magnetic field B, E and δn allows to distinguish among the slow, fast and intermediate MHD wave modes which are of fundamental importance.
- Much of the local wave-particle interaction can be through electrostatic waves that can be seen mainly in E and δn data.
- Many fundamental quantities such as Poynting flux and wave energy require knowledge of B, E and/or δn.
- Of particular interest are E and δn measurements at MHD scales and scales covering characteristic ion scales where MHD starts to break down as these are the scales where ions can be energized.

Before discussing some of the topics in more details we characterize the plasma at perihelion of the Solar Orbiter where most of the science operations will be carried out.

2.1 Plasma parameters at the Solar Orbiter perihelion

The Solar Orbiter orbit is expected to have an elliptical orbit with the perihelion at $\sim 0.22\,\mathrm{AU} \sim 47\,R_\odot \sim 33 \cdot 10^6$m. During perihelion the Solar Orbiter will be close to being in corrotation with Sun and during this time the scientifically most important measurements are carried out. Therefore in the rest of discussion we concentrate on this region.

Typical plasma parameters that can be expected at 0.22AU distance are given in Table 1. The wide range of parameters gives a correspondingly wide range of characteristic scales that are involved in physical processes. Some typical

Quantity	Fast solar wind	Slow solar wind	CME	Total variation
B [nT]	40-80	40-80	40-130	5-500
n [cm^{-3}]	60-100	200-400	50-500	20-1000
v [km/s]	600	350	300-1000	300-1000
T_p [eV]	20-80	2-20	3-50	2-100
T_e [eV]	8-30	1-8	1-30	1-50

Table 1

Typical plasma parameters that can be expected at 0.22 AU distance. The parameters are B magnetic field, n plasma density, v plasma velocity, T_p proton temperature and T_e electrons temperature. Table is partially based on Burlaga (2001); Wang et al. (2005).

values of these scales are given in Table 2. As a rough rule of thumb we can see that characteristic frequencies involving ions - proton gyrofrequency f_{cp}, lower hybrid frequency f_{lh} and ion gyroradius scales dopppler shifted by solar wind - are in the interval from zero to a few hundred Hz. Frequencies depending only on electrons - electron gyrorfrequency f_{ce}, a plasma frequency f_p - are typically at one kHz and above.

2.2 Solar wind turbulence

The understanding of physical processes that leads to solar wind turbulence and its role in coronal heating and solar wind acceleration are major topics in coronal studies (Leamon et al., 2000). As an example, Cranmer (2004) state that "Much what has been done until now is to work backwards, from

Frequencies	[Hz]	Lengths scales	[km]	Velocities	[km/s]
f_{pe}	90,000	λ_D	0.007	V_{te}	3,000
f_{ce}	1,400	ρ_p	13	V_{SW}	500
f_{lh}	30	c/ω_{pi}	23	V_A	100
f_{cp}	0.75	ρ_e	0.3	V_{tp}	60
V_{SW}/ρ_p	40				

Table 2

Typical plasma scales at 0.22 AU distance for plasma parameters B=50 nT, n=100 cm^{-3}, T=20 eV, v=500 km/s. The parameters are f_{pe} (plasma frequency), f_{ce} (electron gyrofrequency), f_{lh} (lower hybrid frequency), f_{cp} (proton gyrofrequency), λ_D (Debye length), ρ_p (proton gyroradius), c/ω_{pi} (ion inertial length), ρ_e (electron gyroradius), V_{te} (electron thermal velocity), V_{SW} (solar wind velocity), V_A (Alfvén velocity), V_{tp} (proton thermal velocity).

the measured plasma parameters deduce the properties of the kinetic-scale fluctuations that would provide the energy" [for extended coronal heating]. They suggest that it is important to look at large scale energy input to the turbulence as a constraint on possible dissipation at smaller scales. At the same time their statement also clearly identicates that there is a large gap in our knowledge of the kinetic fluctuations, particularly at dissipation scales where the energy from the turbulence leads to the dissipation in form of coronal heating. Characteristic dissipation scales are comparable to ion scales, can be both spatial and temporal and from Table 2 we see that it corresponds to frequencies from DC up to about 100 Hz. In situ measurements of these kinetic fluctuation scales are crucial for the understanding of turbulence dissipation mechanisms.

2.2.1 Density fluctuations

Density fluctuations in the solar wind have been studied both *in situ* and remotely. In situ very low frequency density fluctuations have been measured by the Helios spacecraft (Marsch and Tu, 1990). Using the ion instrument and studying the frequency range $6 \times 10^{-6} - 6 \times 10^{-3}$ Hz it is shown that turbulence intensity and development are different in slow and fast solar winds. Similar conclusions have been reached looking at even higher frequency density fluctuations (f<0.6 Hz) as estimated using remote coronal sounding experiments(Efimov et al., 2005). In addition, those observations show spectral breakpoints where density fluctuation spectra flattens out at both low and high frequencies (in the frequency range 0.01-1 Hz). There is a clear dependence of the frequency of spectral breakpoints on the distance from the Sun. This dependence is illustrated in Figure 1. The spectral breakpoints are of particular interest in the turbulence studies as they indicate a change in the turbulence regime and their in situ observations would be crucial to understand the ways density fluctuations are injected and dissipated in the solar wind. Figure 1 suggests that to cover both spectral breakpoints at the Solar Orbiter distance density fluctuations should be measured at least in the frequency range 0.001-10 Hz.

2.2.2 Electric and magnetic field fluctuations

Solar wind turbulence has been mainly studied in situ analyzing magnetic field fluctuations. A major question is how this turbulence leads to heating of the corona. Two major mechanisms that have been proposed are ion cyclotron heating and spectral cascade. In both cases wave electric fields as seen by

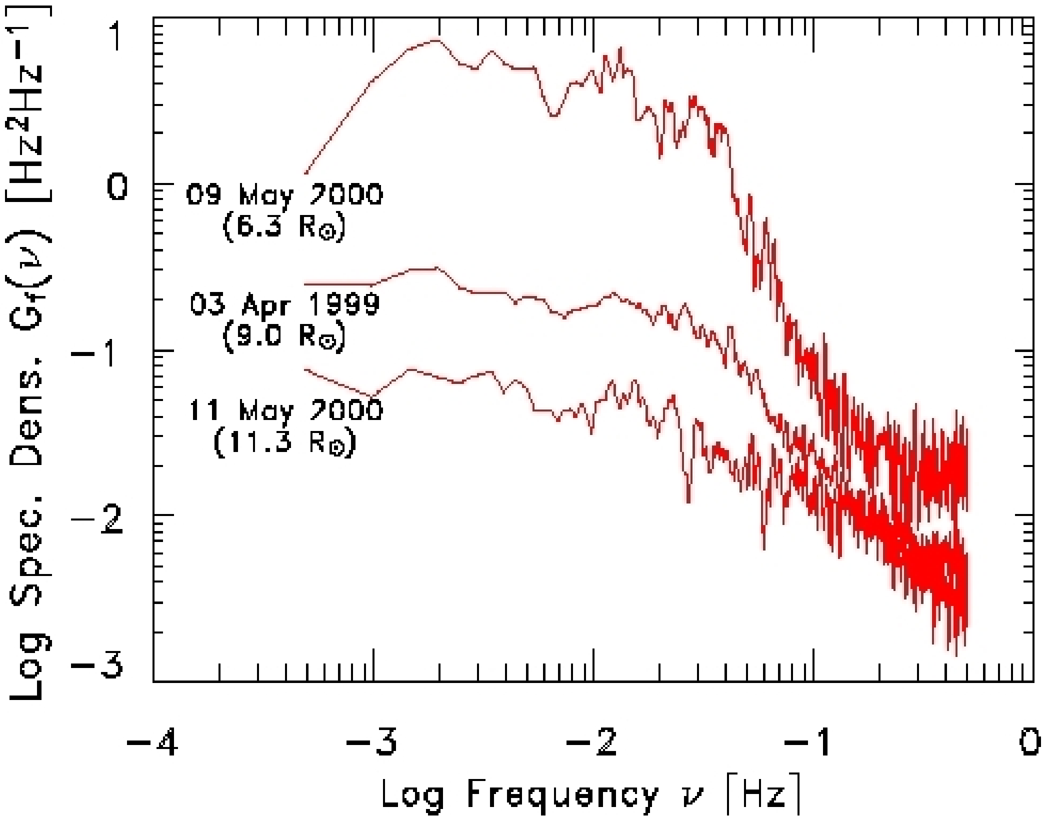

Fig. 1. Density fluctuation spectra as estimated from radio sounding of solar corona during the Galileo spacecraft solar conjunction Efimov et al. (2005). The spectra show two spectral breakpoints where spectra flattens at low and hiqh frequencies. If we look at the high frequency spectral breakpoint as measured at two different distances, 6.3 and 9.0 $R_{\odot}$, one can see that the spectral breakpoint moves to higher frequencies with increasing distance from the Sun, from $\sim$0.2 to $\sim$0.3 Hz respectively when comparing 6.3 and 9.0 $R_{\odot}$ distances. The authors conclude that the high frequency spectral breakpoint at which the density spectra flattens out moves to higher and higher frequencies with increasing distance from the Sun. To measure both the low and high frequency beakpoints at 0.22 AU distance, density fluctuations should be measured in the frequency range 0.001-10 Hz. Figure adopted from Figure 2 in Efimov et al. (2005).

the ions should have significant amplitude at the ion gyrofrequency. In the first case waves at the ion gyrofrequency energize the ions while in the second second case spectral cascade leads to the generation of waves with smaller and smaller wavelength while at some limit efficient damping sets in. A breakpoint in the magnetic field spectra has been used as an indicator when turbulence goes dissipative regime. Detailed analysis of 33 turbulent spectra observed by the Wind spacecraft have shown that the breakpoint is located somewhere between 0.05–0.2 Hz which corresponds to ∼2–3 f_{cp} or ∼0.5–0.7 $V_{SW}(c/\omega_{pi})^{-1}$ (Leamon et al., 2000). The main conclusions from this is that understanding of the turbulence dissipation is not possible without having observations covering frequencies around ion gyrofrequency and covering spatial lengths comparable to the ion inertial lengths scales.

An important question is what kind of measurements would allow to distinguish which of several turbulence models best describes the solar wind. A recent study by Bale et al. (2005) shows that usage of electric field data is crucial for this task. Using Cluster spacecraft data, Bale et al. (2005) obtained the first detailed observations of a breakpoint in spectra from solar wind turbulence using both electric field and magnetic field data. Figure 2 shows the resulting spectra. By combined usage of E and B spectra Bale et al. (2005) could distinguish that at the breakpoint spacecraft were observing wave modes of kinetic Alfvén type, thus supporting the idea of spectral cascade. This was a single measurement that requires further confirmation by spacecraft at 1 AU distance. A major question is if similar mechanisms are operating close to the Sun where the turbulence can still significantly contribute to the extended heating of corona.

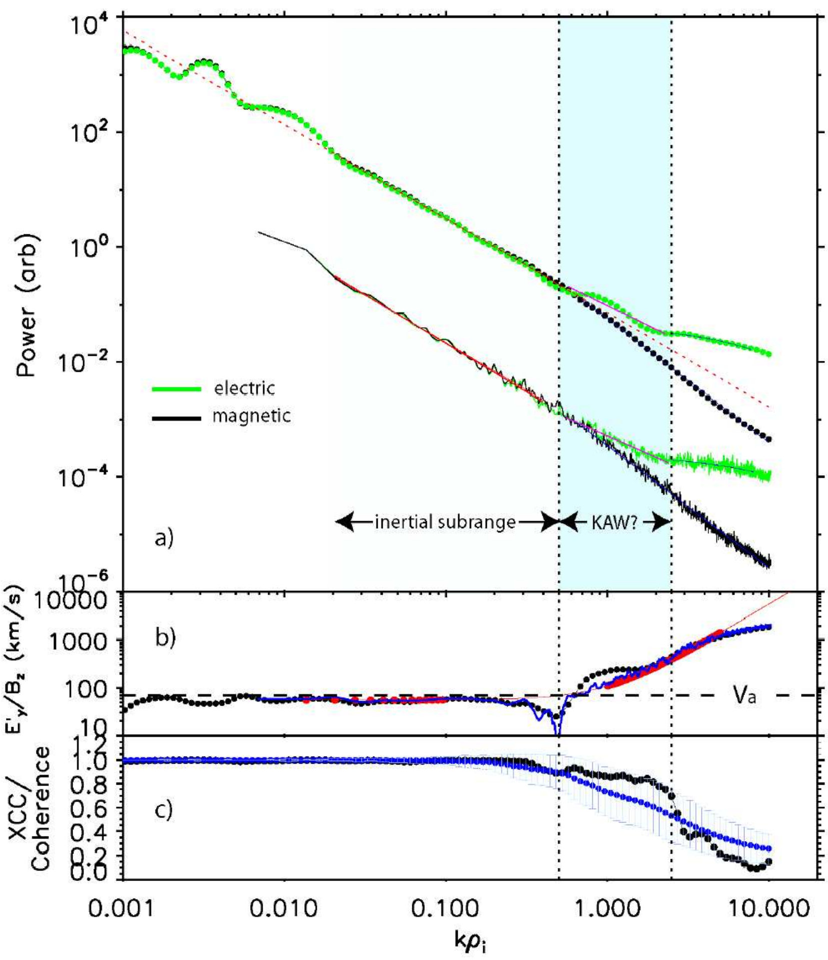

Fig. 2. Figure shows turbulence spectra of B and E fluctuations measured by Cluster s/c in the solar wind. Spectral breakpoint can be seen at wavelength $k\rho_i \leq 1$, at shorter wavelengths spectra becomes more and more electrostatic. Adopted from Figure 3 in Bale et al. (2005).

2.3 Interplanetary Coronal Mass Ejections (CME)

Interplanetary shocks driven by CMEs are a source of Type II solar bursts. Understanding CMEs and Type II solar bursts is important for being able to predict CMEs, that in turn are a major cause of geomagnetic storms. Theoretically predicted behaviour of emissions depends on shock parameters (Knock et al., 2003). The exact generation mechanisms of the electromagnetic radiation are not clear. Mechanisms such as Langmuir wave interaction with ion acoustic waves or Langmuir wave conversion at density gradients have been suggested. In addition, the bursts can have complicated internal structure suggesting that most probably different generation mechanisms can be at play in parallel. Shocks involve fast changes in density, and localized electric fields on ion scales. Also ion acoustic waves are on ion scales. Thus, high time resolution E, B and density fluctuation measurements are needed to study these phenomena.

2.4 Reconnection

Magnetic reconnection is one of the fundamental processes that needs to be better understood to make significant progress in explaining energy conversion, transport and other processes in the solar atmosphere. It is involved on all scales, starting from CMEs where it is believed to be crucial for allowing CMEs to escape the Sun and ending with the smallest scales where microreconnection can be one of the ways energy is dissipated in solar wind turbulence.

Recently several studies have been presented analyzing local magnetic reconnection events in the solar wind at 1 AU distance (Gosling et al., 2005; Phan et al., 2006). All these events were associated with narrow current sheets forming behind CMEs, see Figure 3. Similar remote observations of reconnection have been done using SOHO spacecraft observations at distances close to the Sun (Lin et al., 2005). The SOHO observations show that narrow extended current sheets form behind the CMEs and reconnection is ongoing within those current sheets starting from a few solar radii distance from the Sun. The Solar Orbiter would be optimally located to see the temporal evolution of the recon-

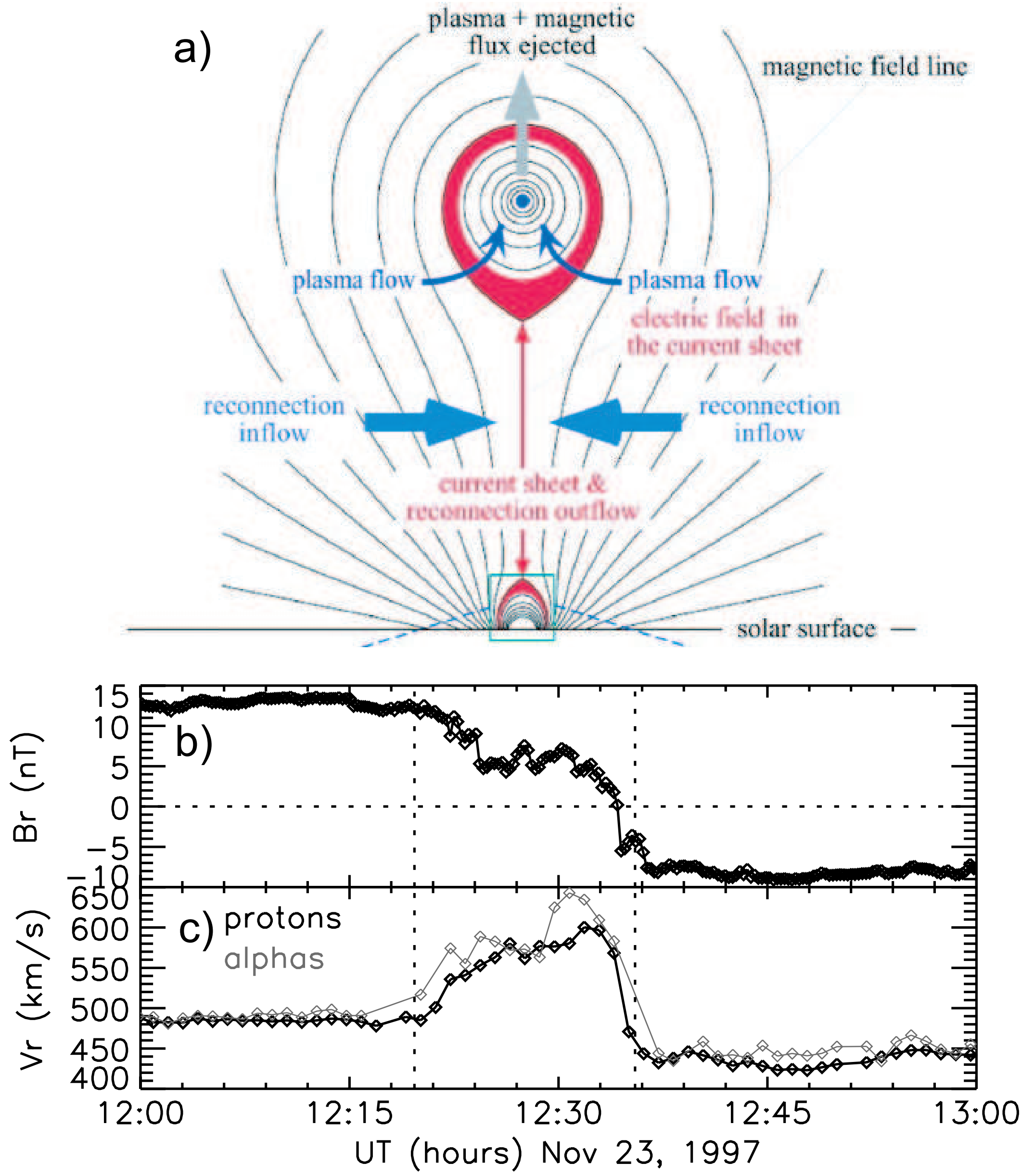

Fig. 3. *In situ* reconnection jet observations in the solar wind. a) a sketch of narrow current sheet formation behind CMEs, adopted from Figure 1 in Lin et al. (2005). b,c) in situ observations by ACE, b) shows the reconnecting component of magnetic field and c) shows the presence of a reconnection jet in both protons and alphas, adopted from Figure 3 in Gosling et al. (2005).

nection processes within these current sheets. The reconnection process can be identified using only particle instruments, however, E field measurements are needed for the understanding of reconnection process as is well known from the studies in the Earth magnetosphere (Vaivads et al., 2006). For example, to understand how different particle species are energized during the reconnection process, one needs to have information on fields on characteristic scales of those particles, particularly E because particles are energized by the E field. Also when slow shocks or other discontinuities are involved one needs to have E measurements to be able to estimate potential jumps across the discontinuities.

3 The Solar Orbiter in context with other missions

Several satellites have performed plasma measurements in the solar wind. However, few missions with comprehensive plasma instrumentation have been dedicated for solar and/or solar wind science and have had instruments to measure electric field and/or density fluctuations. Notable exceptions include Ulysses and Wind.

Ulysses was launched in 1990 on a trajectory toward Jupiter, whose gravity was used to put the spacecraft in a polar orbit around the Sun. To date the Sun has been circled twice. Ulysses included a 72-m tip-to-tip dipole antenna and a 7.5 m spin-axis monopole for electric field measurements. In addition the spacecraft carried a flux-gate magnetometer. Both the electric field and the magnetic field signals were fed into a Wave Form Analyzer that performed spectral analysis in the range 0.08 to 448 Hz, in addition to measurements at higher frequencies.

Wind was launched in 1994 and has spent most of its time since launch in the near-Earth solar wind. Wind measures the electric field using two pairs of wire dipole antennas in the spin plane and one pair of rigid antennas along the spin axis. A low-frequency FFT receiver covers the frequency range DC - 10 kHz. There are also higher frequency receivers.

In addition to spacecraft dedicated to solar wind studies, there have been many spacecraft that have had the Earth magnetosphere as a major objective but the instrumenation of which have allowed detailed studies of electric field and density fluctuations in the solar wind. Examples are Cluster, Geotail, Polar, etc. Particularly multi-spacecraft capabilities of Cluster have proven very valuable as shown by the turbulence example in previous section.

Measurements of electric field and density fluctuations in solar wind at distances less than 1 AU are lacking. In principle, spacecraft bound for Venus should be useable for exploring the solar wind in the inner heliosphere. However, from a plasma point of view these spacecraft are usually not very well instrumented.

Among future solar missions, Stereo (launch 2006) and Solar Wind Sentinels (AO 2006) are the ones planned to carry the most comprehensive plasma instrumentation. Stereo is focused on solar radio bursts. It does have the capability to measure waves also at lower frequencies, but the extent to which this will be pursued is unclear. Solar Wind Sentinels is a comprehensive multi-spacecraft mission to fly inside of Earth's orbit, focusing on providing some capability of space weather predictions.

BepiColombo will have a comprehensive plasma payload including low-frequency wave measurements. The spacecraft will only spend part of its orbit around Mercury in the solar wind and thus will not offer the opportunity of continuous monitoring of solar wave emissions in the low-frequency domain. However, assuming the two missions coincide in time, BepiColombo may be a nice complement to Solar Orbiter, off and on providing a vantage point at a different heliospheric longitude.

Past and planned missions taken into account, Solar Orbiter will provide a unique opportunity of continuous in-situ measurements of low-frequency wave activity in the solar wind, at solar distances where the observed waves may be remnants of the coronal heating processes. Furthermore, Solar Orbiter will at times co-rotate with the solar surface. Finally, in addition to the plasma measurements, Solar Orbiter will perform optical measurements in a wide range of wavelengths, thus providing context for the interpretation of the wave measurements regardless of the spacecraft's location relative to Earth and terrestrial solar observatories.

4 Instrumentation

As demonstrated in the previous Sections, information on electric field and plasma density fluctuations at high time resolution is needed for proper understanding of important dynamical processes in the corona and solar wind. To obtain such measurements, we here propose a double-probe instrument, with electronics for the measurement of electric fields from DC up to $\sim$1 kHz and sharing antennas with an instrument measuring waves at higher frequencies. As a by-product, such an instrument also gives information on plasma density fluctuations at high time resolution, by use of the spacecraft potential. Additional plasma diagnostics could also be obtained from use in Langmuir probe mode.

Double-probe instruments are widely used for measurement of electric fields in the terrestrial environment. In denser ionospheric plasmas, the probe potential is often floating (Maynard, 1998), while instruments useful in the tenuous plasmas in the magnetosphere and solar wind use a technique based on sending a fixed bias current to the probes (Pedersen et al., 1998). To minimize perturbations from the spacecraft carrying the instrument, one usually measures the voltage between two identical probes mounted at the tips of long booms protruding from the spacecraft. In the ideal case, the boom length should exceed the Debye length, to ensure small influence of any electrical perturbations from the spacecraft. In practice, useful measurements can be obtained also in more tenuous plasmas, for reasonably symmetric spacecraft and carefully designed electrical neighbourhood of the probes. The latter neighbourhood usually consists of elements bootstrapped to the probe potential plus or minus some offset value, ensuring that the potential at the probe is not just determined by the boom potential.

To optimize the use of scarce spacecraft resources, it is likely desirable to use the same booms for LF and HF measurements. This can be achieved in several ways. One way is to use the LF probes also as monopole antenna elements for the HF instrument, as is very successfully done on for example the Cluster satellites (Gustafsson et al., 1997; Gurnett et al., 1997). However, the frequency range that can be achieved in this way without having preamplifiers out on the boom, close to the probes, is likely insufficient for an HF instrument. Another way is to use the outer shield of the booms themselves as antennas for the HF instrument, while the probes are mounted on the tip of the booms (or actually constituted by the boom tips, see below).

For solar wind measurements, booms much in excess of the Debye length (5 –

10 m, see Table 2) can be achieved only as wire booms on spinning spacecraft. However, solid booms with lengths of order 5 m are certainly feasible, and given a reasonably symmetric spacecraft with a conductive surface and an careful design of probe and adjacent biased parts, good electric field measurements can be obtained with such booms. In order to investigate polarization properties of waves and a reasonably complete picture of the electric field, measurements in two dimensions are needed. This means a minimum of three booms, which could be arranged as suggested in Figure 4a. From the differences between two pairs of probes, for example 1-2 and 1-3, a 2-D E-field can be constructed. However, a more symmetric arrangement would be obtained using four booms as in arrangement Figure 4b. This also brings all probes away from any wake and Mach cone structures forming around the spacecraft. The higher degree of symmetry and longer baseline as compared to Figure 4a should also offer advantages for an HF instrument, though at the cost of the loss of the possibility of obtaining three-dimensional measurements using each boom as a monopole antenna offered by the arrangement in Figure 4a. The 3D capability is restored using the configuraton Figure 4c, with one boom pair angled towards the Sun at around 45 deg. Other possibilities may also be considered, and the final choice of boom configuration will need to take into consideration how to minimize influence of wake effects, asymmetries and spacecraft photoelectrons on the LF measurements under the constraints posed by the needs of the HF instrumentation and the spacecraft resource budget.

On a non-spinning spacecraft with a well defined symmetry direction for photoemission causing UV radiation as well as for plasma flow, as both comes from the Sun, cylindrical probes could be used. This amounts to using the outermost

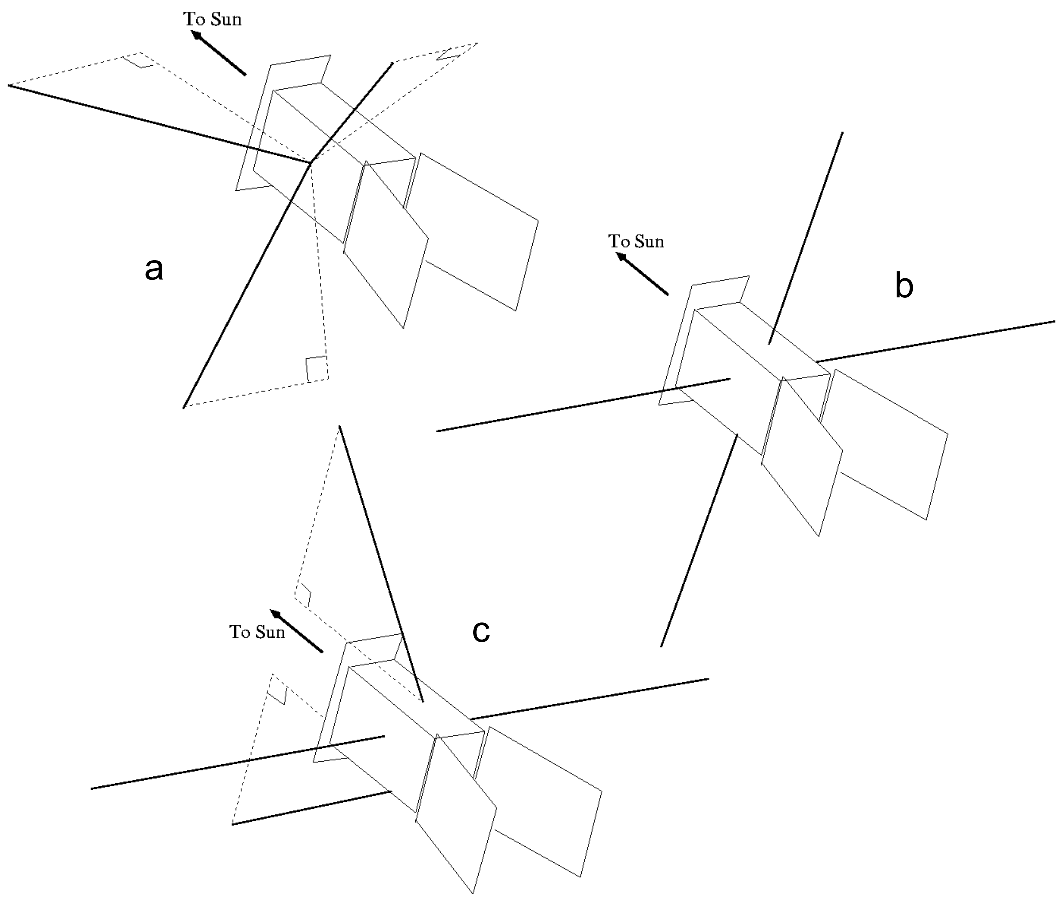

Fig. 4. Some possible Solar Orbiter boom configurations. In each case, the outermost part is used as electric field probes.

part of the boom as a probe. Depending on boom thickness, a probe length of 10 - 20 cm could be considered, with some adjacent biased (bootstrapped) elements. Probe arrangements of this kind, including the cylindrical geometry, will be used on the EFI instrument on the upcoming THEMIS mission, and are planned also for the MMS FIELDS instrument. The EFI instrument on the POLAR satellite (Harvey et al., 1995) has stiff axial booms of similar size, but uses spherical probes, which would be an uneccessary mechanical complication in our case. Nevertheless, the axial booms of POLAR EFI is a close analogue of one pair of booms in Figure 4b.

5 Conclusions

Solar Orbiter is an ESA mission planned to take high resolution images of the Sun and perform the closest ever in situ observations of solar wind. Several major scientific questions can be addressed by observing electric field and density fluctuations from low frequencies up to around one kHz. This frequency range include waves essential for wave-particle interaction involving ions (the ion gyrofrequency and the lower hybrid frequency) and also ion scales (the ion gyroradius) Doppler shifted by the solar wind motion as seen in the spacecraft frame.

One important question is what models best describe the fluctuations on ion temporal and spatial scales in the solar wind, and how these fluctuations are dissipated to heat ions and electrons. Here clearly observations of density and electric field fluctuations are needed, together with measurements of the magnetic field at the same frequencies, to obtain scientific closure. Another example is the generation of electromagnetic waves such as Type II solar bursts from interplanetary shocks. These waves are interesting since they can be used for remote sensing once their generation is understood. This generation most likely involves rapid density variations and localized electric field which can be detected in situ by Solar Orbiter. Magnetic reconnection is a phenomenon believed to be important for the escape of CMEs, and at much smaller scales may be important for local energy dissipation. As is known from studies in the terrestrial magnetosphere, observations of small scale density and electric field structures are essential for understanding reconnection in a new parameter regime.

As any exploratory spacecraft, Solar Orbiter will have limited resources for the payload. To optimize the use of resources, one must seriously consider using the same antennas over the whole frequency range of interest. We find that using reasonable compromises it is possible to use the same payload to detect small scale and low frequency density and electric field fluctuations, and to observe electric fields at frequencies of several MHz.

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