DOCUMENT

SOLAR ORBITER

SCIENCE REQUIREMENTS DOCUMENT

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1. INTRODUCTION

The Sun's atmosphere and the heliosphere represent uniquely accessible domains of space, where fundamental physical processes common to solar, astrophysical and laboratory plasmas can be studied in detail and under conditions impossible to reproduce on Earth or to study from astronomical distances.

The results from missions such as Helios, Ulysses, Yohkoh, SOHO, TRACE and RHESSI have advanced significantly our understanding of the solar corona, the associated solar wind and the three-dimensional heliosphere. Further progress is to be expected with the launch of STEREO, Solar-B, and the first of NASA's Living With a Star (LWS) missions, the Solar Dynamics Observatory (SDO). Each of these missions has a specific focus, being part of an overall strategy of coordinated solar and heliospheric research. An important element of this strategy, however, has yet to be implemented. We have reached the point where further *in-situ* measurements, now much closer to the Sun, together with high-resolution imaging and spectroscopy from a near-Sun and out-of-ecliptic perspective, promise to bring about major breakthroughs in solar and heliospheric physics. The Solar Orbiter will, through a novel orbital design and an advanced suite of scientific instruments, provide the required observations.

The unique mission profile of Solar Orbiter will, for the first time, make it possible to:

- Explore the uncharted innermost regions of our solar system;
- Study the Sun from close-up;
- Fly by the Sun tuned to its rotation and examine the solar surface and the space above from a co-rotating vantage point;
- Provide images and spectral observations of the Sun's polar regions from out of the ecliptic.

Within the framework of the global strategy outlined above, the top-level scientific goals of the Solar Orbiter mission are to:

- **Determine the properties, dynamics and interactions of plasma, fields and particles in the near-Sun heliosphere;**
- **Investigate the links between the solar surface, corona and inner heliosphere;**
- **Explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere;**
- **Probe the solar dynamo by observing the Sun's high-latitude field, flows and seismic waves.**

These specific goals are directly related to more general questions of relevance to astrophysics in general. For example: Why does the Sun vary and how does the solar dynamo work? What are the fundamental processes at work in the solar atmosphere and heliosphere? What are the links between the magnetic field-dominated regime in the solar corona and the particle dominated regime in the heliosphere?

The near-Sun interplanetary measurements together with simultaneous remote sensing observations of the Sun will permit us to disentangle spatial and temporal variations during the co-rotational phases. They will allow us to understand the characteristics of the solar wind and energetic particles in close linkage with the plasma conditions in their source regions on the Sun. By approaching as close as 48 solar radii, the Solar Orbiter will view the solar atmosphere with unprecedented spatial resolution (0.5 arcsec pixels, equivalent to ~80 km at 0.222 AU). Over extended periods, the Solar Orbiter will deliver images and data of the polar region and the side of the Sun not visible from Earth. This latter aspect of the mission is a key factor in

Solar Orbiter's role as a Solar Sentinel within the framework of the International Living With a Star (ILWS) initiative.

In Chapter 2, the top-level scientific goals of the Solar Orbiter 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, the performance requirements per type of payload instrument are specified. It should be noted that, because of the varying spacecraft-Sun distance throughout each orbit, the spatial resolution requirements on the measurements to be made by the remote-sensing instruments are generally expressed in terms of the equivalent pixel size in arcsecs. For example, 0.5 arcsec pixel size translates to a linear scale of ~80 km on the solar surface when the spacecraft is at its closest distance of 0.222 AU from the centre of the Sun. The size of the smallest resolvable feature in this case is then ~160 km.

The implementation of these requirements in the form of actual instruments will be described in the Payload Definition Document (PDD).

2. SCIENTIFIC REQUIREMENTS

2.1 Determine the Properties, Dynamics and Interactions of Plasma, Fields and Particles in the Near-Sun Heliosphere.

According to the SOHO findings, one must conclude that the open corona mainly expands because of the very high temperatures of the coronal ions, with the minor species reaching several 10 MK at a few solar radii. In contrast, electrons are comparatively cool, in fact they are found to hardly reach the canonical coronal temperature of 1.5 MK, and consequently the electric field (related to their pressure gradient) has a minor role in the acceleration. The high pressure of the coronal ions, and the low pressure of the interplanetary and interstellar ions, leads to a rapid coronal expansion and a supersonic solar wind. Yet, even after the SOHO mission, the detailed physical mechanisms that heat the corona and accelerate the bulk plasma and minor energetic particles remain poorly understood. Since the Helios mission, the solar wind has never again been measured close to the Sun (Helios perihelion 0.3 AU).

The Solar Orbiter will provide a new opportunity of going close to the Sun and into the inner heliosphere (to 0.222 AU), and unlike Helios and Ulysses, it will carry powerful, high-resolution optical instruments together with modern *in-situ* instruments. In particular, the plasma and field instruments will have high temporal resolutions (up to 0.1-3.0 s), and thus offer unique possibilities for resolving plasma kinetic processes at intrinsic scales. Therefore, Solar Orbiter will reveal new insights into the processes that structure the Sun's atmosphere, heat the inner corona and accelerate the solar wind and energetic particles, and also into the manifestations of the solar output into the inner heliosphere.

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

2.1.1 What is the character and radial evolution of solar wind structures in the inner heliosphere?

2.1.1.1 How do solar wind structures evolve in the inner heliosphere?

The innermost regions of the heliosphere set up the conditions for further evolution of the solar wind into the heliosphere. While we understand the processes that govern the evolution, we don't know these inner boundary conditions. Source surface mapping techniques make many assumptions whose justification has not been proved. For instance, potential field models assume current-free and force-free expansion of the coronal plasma. The assumption that there are no currents flowing in the solar corona is almost certainly not true. The implications of this disconnect are not clear, but will certainly produce discrepancies between source-surface models often used to model the extension of the corona out to the inner heliosphere and real inner heliospheric structure. Hence direct measurements of the structure and dynamics of the inner heliosphere are of great importance to the understanding of the propagation of coronal structures into the heliosphere.

2.1.1.2 How fast do different coronal structures expand?

As expected, SOHO/LASCO and UVCS observations clearly show that coronal holes expand super-radially, and that streamers too, have regions of super-radial expansion. However, as a white light imager, LASCO sees only density contrast and cannot infer the actual flows in coronal holes. Does the solar wind truly flow in the dark regions of coronagraph images, and even if it does, how does this flow extend out beyond coronagraph fields of view? Answering this question requires *in-situ* heliospheric measurements of the solar wind plasma with correlated remote-sensing measurements from other spacecraft.

2.1.1.3 What is the structure of the heliospheric magnetic field inside 1 AU? How does the heliospheric current sheet form and evolve? How is it embedded in the slow solar wind?

Measurements at 1 AU suffer from dynamic modifications of the vicinity of the current sheet. Only Solar Orbiter will be able to measure this structure-defining sheet in a near-undisturbed state, facilitating inferences about its properties.

New scenarios for the magnetic structure of the heliosphere predict variations of plasma properties, including variations in composition along a field line, while the classical Parker picture would not produce such variations. By measuring the detailed solar wind properties including elemental and charge state composition of the solar wind on single flux tubes, Solar Orbiter will allow us to distinguish between competing scenarios.

<u>Measurement Requirements:</u>

- Low-cadence measurements of the inner heliospheric plasma properties including composition, and fields.
- White-light coronagraph observations of the outer coronal structures, which could be possibly enhanced by UV outer coronal observations and possibly with a spectroscopic capability.
- Supporting low coronal EUV imaging for context observations of underlying coronal structure, and EUV spectroscopy, for context observations of flows and ion composition – both with modest to low-cadence and resolution.

2.1.2 What is the nature of solar wind stream interactions in the inner heliosphere, and how does it depend on latitude?

The boundaries between different solar wind streams are indicated both by differences in the kinetic properties of the solar wind and by its composition. The nature of these boundaries is not well understood. While such stream interfaces have been measured at 1 AU and between 3 and 5 AU, their nature can be much better investigated well inside 1 AU, because the dynamic processes occurring within and beyond 1 AU wipe out the pristine signatures of these interfaces. It is currently not known whether these interfaces are sharp or gradual and whether they are the same for fast wind running into slow wind (compressions) and for slow wind being left behind by fast wind (rarefactions). Previous studies of these latter rarefaction regions at high latitudes, where compression effects are diminished, show a relatively smooth transition in ion freezing-in temperature associated with solar wind acceleration, but a sharp discontinuity in elemental composition that is probably fixed at lower altitudes in the chromosphere and corona.

Solar Orbiter will be able to make definitive observations of such boundaries, allowing separation of the effects of solar wind acceleration and source region structure.

<u>Measurement Requirements:</u>

(These observations would be especially important during the closest approaches of Solar Orbiter to the Sun.)

- Burst mode data for electron and proton 3-D velocity distribution functions, high-cadence ion composition data, magnetic field vectors, during boundary crossings (considerably less time resolution is required outside the crossings).
- White-light coronagraph (and possibly UV) outer coronal observations for context data for boundary identification.

2.1.3 What is the influence of CMEs on the structure of the inner heliosphere?

Coronal mass ejections (CMEs) play a major role in structuring the heliosphere during solar activity maximum, as is witnessed by the countless Forbush decreases recorded by neutron monitors world wide in the past half century. However, such measurements only characterize the response of the *outer* heliosphere to these disturbances, the reaction of the *inner* heliosphere has been explored to a considerably lesser extent.

The propagation of coronal mass ejections into the heliosphere may be accompanied by ongoing reconnection within the innermost heliosphere. Observation of this process by Solar Orbiter would allow the first *in-situ* observation of magnetic reconnection outside the Earth's magnetosphere and would have a dramatic influence on widely differing fields such as solar physics, astrophysics, and heliospheric physics.

Coronal mass ejections often drive shock waves that in turn propagate through the heliosphere. They are thus an important structuring agent for the heliosphere. How do they influence the inner heliosphere? How strong are shocks in the inner heliosphere? The fast magnetosonic speed is higher near the Sun than at 1 AU, the magnetic field is nearly parallel to the shock normal; hence it is more difficult to have strong shocks inside 1 AU than outside. Solar Orbiter will help to answer these questions.

<u>Measurement Requirements:</u>

- High-cadence (burst-mode) in-situ measurements of electrons, protons, composition and magnetic field during passage of CME shocks, pressure waves, and boundaries.
- Supporting coronagraph observations to identify CMEs and CME structure.
- Supporting EUV low coronal imaging and spectroscopy of solar disk, to identify CME onsets through detection of ejecta, coronal dimming events etc.

2.1.4 What are the sources of solar energetic particles in the heliosphere, and what are the processes responsible for their acceleration?

The Sun is the most powerful particle accelerator in the solar system, producing ions up to tens of GeV and electrons up to 100 MeV energy. The ubiquity of suprathermal particles in the solar atmosphere, as revealed by radio and X-ray observations, and in the solar wind further shows that particle acceleration is a fundamental process in the corona. We have a broad understanding that the magnetic restructuring of active regions and their environment in the course of flares or in the aftermath of CMEs and the shock waves driven by fast CMEs accelerate particles.

The Sun provides the ideal laboratory for studying these processes, which likely also operate in other astrophysical contexts. Inner heliospheric observations (within one particle mean free path, a few tenths of an AU, of the source) of the energy spectrum, angular distribution, and composition of accelerated particles from solar-wind energies to above 100 MeV/nucleon, are critical for understanding how the particles are accelerated and how they propagate into the heliosphere. This in turn is pre-requisite to understanding why and how large fluxes of energetic particles eventually produce significant radiation damage in space electronics, and are a hazard for manned space flight and polar airline flights.

Solar Orbiter can uniquely address the fundamental physics of the acceleration and propagation of solar energetic particles:

- Observing close to the Sun and in the vicinity of the acceleration regions in the inner heliosphere, Solar Orbiter will make nearly pristine observations of solar energetic particles, with minimal modification by interplanetary transport.
- During the phases of near corotation, it will make particle measurements under nearly identical conditions for the transport during successive particle events.
- By combining in situ measurements with remote sensing of energetic electrons and ions through hard X-ray, gamma-ray and neutron observations, it will be able to differentiate between energetic particle populations of different origins.
- By context-imaging observations of coronal plasma-magnetic-field structures, it will track the magnetic field evolution in regions of the corona where acceleration is expected to occur.

<u>Measurement Requirements:</u>

- Energy spectrum, angular distribution, and composition of energetic particles
- High-resolution plasma and field data for shock analysis
- Neutrons, gamma rays and x-rays to provide source diagnostics
- Decametric-to-hectometric radio spectroscopy to identify the magnetic connectivity of the spacecraft and the timing of electron release in the corona.

2.1.4.1 What is the role of shocks and flares in accelerating particles near the Sun?

Large solar energetic particle events are accompanied by both CMEs and flares, and there is a variety of potential accelerators, comprising e.g. the CME-driven shock, magnetic reconnection in the flaring active region in the low corona, and reconnection at greater altitudes, due to the relaxation of the magnetically stressed corona in the aftermath of a CME. Not all particles escape from the Sun, and the relative efficiency of CME-related shocks and flares as particle accelerators is not well known.

There are three key means of distinguishing energetic particle populations with Solar Orbiter: comparative timing, comparative analyses of the composition and energetics of the particles, and context imaging of dynamical structures in the corona.

- In order to distinguish different particle populations through timing, remote sensing observations of particles in the solar atmosphere must be compared with in situ measurements, whereby the influence of propagation on the particle flux profiles is minimized. This requires in situ measurements close to the Sun.
- Neutrons and γ-rays are produced by nuclear reactions of precipitating coronal ions and protons, which are primarily accelerated in magnetically active regions and then collide with the constituents of the denser lower atmosphere of the Sun. Hard X-rays are emitted through bremsstrahlung of energetic electrons. These processes are well understood and will characterize the composition, number and energy spectra of the interacting solar particles, to be compared with the measurements made in situ.
- Magnetography of the photosphere and imaging of the coronal plasma-magnetic field structures at EUV and optical (coronagraph) wavelengths will provide context information on the evolution of acceleration sites in the low corona.

Solar Orbiter will be the first to measure the time evolution of composition, charge states and energy spectra close to the Sun, to tie the arrival of particles at the spacecraft to coronal events via the radio emission of electron beams, and to have a complementary remote-sensing package to probe the interacting particles and the solar context in which they evolve. The contribution of the neutron measurements to this diagnostic is pioneering (cf. Sect. 2.1.5).

Measurement Requirements:

- Charge-state and elemental composition of particles from highest energies down to solar wind energy; ^{3}He must be resolved
- Radio spectrography from the high corona (corresponding to about 20 MHz) to the local plasma frequency (at 10 kHz) with few seconds time resolution and $\Delta f/f \sim 10\%$
- Hard X-ray imaging spectrography at 3-150 keV, with moderate resolution (2.5 arcsecs), energy resolution $\Delta E/E \sim 20\%$; temporal resolution (burst mode) a few seconds
- Gamma-ray measurements from 0.3 to 10 MeV with moderate energy resolution ($\Delta E/E \sim 5\%$) and sensitivity; temporal resolution (burst mode) a few seconds
- Context imaging (EUV in at least 2 bands) of the whole Sun with spatial resolution of a few arcsec or better, cadence a few tens of seconds; coronagraph very highly desirable

Further desirable measurements:

- Isotopic composition.

2.1.4.2 Shock Acceleration from 0.22 AU to 1 AU

In-situ measurements at 1 AU show that collisionless shock waves accelerate electrons and ions to energies of several keV and some MeV, respectively. But it is not known if and how rapidly shocks can accelerate solar energetic particles to relativistic energies in the corona and inner heliosphere. The controversy about the importance of flares and CME-driven shocks in the production of solar energetic particles also partially stems from the lack of knowledge and understanding of the source population, which is further accelerated in CME-driven shocks. Besides the ambient corona or solar wind, the supra-thermal particles from previous flares may also be part of the source population.

By measuring the composition of accelerated and ambient particles and the parameters of the shock waves across a range of acceleration sites between 0.22 and 1 AU, Solar Orbiter will study shock acceleration and the evolution of its efficiency as a function of the ambient plasma parameters. Measurements of the energy spectrum, angular distribution, and composition of the freshly accelerated particles, from solar-wind energies to above 100 MeV/nucleon, are required for understanding the acceleration process. Measurements of the upstream waves are crucial, and require a high-time-resolution memory, since the shock wave will go past the spacecraft in seconds or less.

Measurement Requirements:

- Composition from highest energies down to solar wind
- Correlated remote-sensing and in-situ observations
- Angular distributions and spectra of electrons and ions, spectra of plasma waves with high temporal resolution
- Radio spectrography as an indicator of shock waves in the corona
- Coronagraph very highly desirable.

2.1.4.3 Transport Phenomena

The propagation of solar energetic particles is still mostly discussed in terms of the Parker field picture, without considering the dynamics of the magnetic field, i.e. the wandering of interplanetary field line or large-scale reorganization of the coronal magnetic field in the course of CMEs. Ulysses measured energetic particles at high latitudes on field lines which could not be magnetically linked to the probable acceleration sites in the Parker picture. The comparatively simple magnetic structure of the inner heliosphere will facilitate to test the magnetic connection of an (in-situ) observation point with a particle acceleration site. This will allow studies of the transport properties of energetic particles, especially of the relative importance of diffusion along and perpendicular to the magnetic field. Current theory predicts a ratio of $\kappa_{par}/\kappa_{perp}$ ~10, however, measurements seem to indicate that this ratio can approach unity in some cases. Testing the scattering (and hence diffusion) properties of energetic particles in the inner heliosphere will have implications both for heliospheric physics and astrophysics, especially for the numerical modelling of cosmic ray propagation and theoretical understanding of particle scattering by turbulence.

By taking advantage of the near-corotation parts of several orbits, Solar Orbiter will observe repeating particle events in a nearly constant geometrical configuration. Modifications of the escape conditions from coronal acceleration sites will perhaps mostly be due to changing magnetic configurations on the Sun, which will be probed by magnetic-field measurements in the photosphere and EUV imaging of the plasma and magnetic field in the corona. At the same time, hard X-ray imaging will allow us to infer the sites of electron acceleration in the low corona, and radio-wave spectroscopy to trace the escape of electrons from the corona.

Measurement Requirements:

- Pitch-angle distributions, directional rates of energetic particles
- Magnetic field measurements for turbulence studies
- Coordinated remote-sensing and in-situ observations
- Radio spectrography of electron beams, local Langmuir waves

Further desirable measurements:

- Composition to constrain rigidity dependence.

2.1.5 What are the fluxes and spectra of low-energy solar neutrons?

Solar neutrons are produced in flares by nuclear reactions caused by energetic protons, which penetrate the dense lower layers of the solar atmosphere and cause spallation reactions with alpha particles. Because of the beta decay, the resulting neutron flux varies dramatically with distance from the Sun: the maximum distance neutrons can reach is equal to the product of their speed and mean lifetime (~8 minutes for non-relativistic neutrons). In fact, at Earth orbit, neutrons with energies less than 100 MeV cannot be detected at all. Very few solar neutron events have been reported, as compared with several hundreds of events of γ-rays, which may be formed by thermal reactions of neutrons with protons, which fuse and form deuterium. During the perihelion passages, Solar Orbiter will measure for the first time the low-energy neutrons directly.

Solar Orbiter will thus open a new window to the Sun: solar neutron astronomy. The advantage of neutrons over charged particles is that they travel in straight lines and, unlike ions, are not delayed because of the complicated paths prescribed by the magnetic field lines. Temporal correlations are therefore easier.

Measurement Requirements:

- Solar neutrons in the range from 1 MeV to ~ 100 MeV
- The flux of solar γ-rays, which are produced and emitted in the form of the 2.2 MeV line during the nuclear production of deuterium
- Context surface EUV imaging.

2.1.6 How does the solar wind microstate evolve with radial distance?

The expansion of the solar corona into interplanetary space is accompanied by a multitude of microscopic plasma processes. While the solar corona sets the inner boundary, the ongoing processes alter this state in ways that are currently not well understood but of fundamental importance to heliospheric physics, astrophysics, and plasma physics in general. While stream-stream interactions play an important role, the relaxation of non-Maxwellian velocity distribution functions and the heating by various waveforms is also an important factor, underlining the importance of wave-particle interaction in the understanding of the physics of the heliosphere. The comparatively simple structure of the inner heliosphere makes it an ideal candidate for the study of plasma-physical phenomena that are otherwise not accessible, neither in the laboratory, nor in other astrophysical plasmas.

2.1.6.1 Kinetic Physics, Wave-Particle Interaction, Coulomb collisions

Wave-particle interactions are the principal scattering agent for heliospheric particles and extremely important for the acceleration of the solar and of stellar winds. However, the theoretical treatment of this interaction is extremely complicated and marred by lacking observational "rules of thumb". Further progress on the understanding of astrophysical phenomena such as cosmic-ray transport or particle acceleration and transport depends on further understanding of wave-particle interactions beyond the standard quasi-linear theory.

The heliosphere seems to be divided into three parts, in which wave-particle interaction, Coulomb collisions, and wave-particle interactions in turn are the dominant microphysics process. In the solar corona, the absorption of ion-cyclotron waves appears to heat the solar wind, and at large heliocentric distances, the ion kinetic temperatures appear to be strictly mass proportional, again indicating heating by wave-particle interactions. However, in the vicinity of 1 AU, there appears to be a third regime where Coulomb collisions dominate and tend to equalize ion temperatures. Where does wave-particle interaction cease to heat ions in the inner heliosphere? Why? These are questions that will be addressed by Solar Orbiter.

Measurement Requirements:

- High-cadence, 3-D velocity distribution functions of electrons, protons, alpha particles and abundant heavy ions such as O^{6+} and, if possible, a low Fe charge state such as Fe^{9+} or Fe^{10+}.
- Heliospheric magnetic field vectors.

Further desirable measurements:

- UV coronal spectroscopy providing velocity distribution functions of protons and abundant heavy ions, such as O^{5+}.

2.1.6.2 Generation of Turbulence and its Radial Evolution

The large variation in latitude and heliocentric distance of Solar Orbiter will allow unprecedented studies of the structure and evolution of MHD turbulence. The dominant contribution will come from (incompressible) Alfvénic fluctuations with a minor compressible contribution from stream-stream interactions.

There are three key questions that can be addressed with Solar Orbiter:
- How is turbulence created?
- How does turbulence evolve radially?
- How does turbulence vary with vicinity to stream interfaces?

Measurement Requirements:

- High-cadence plasma, radio, and magnetic field measurements, including
  - 3-D velocity distribution functions of in-situ electrons, protons, and alpha particles.
  - 3-D distribution functions of a few heavy ion species.
- White-light coronagraph outer coronal observations for context data on coronal structure.
- EUV imaging of a large field of view, to study magnetic structure of the corona.

2.1.6.3 Links to Coronal Heating and Solar Wind Acceleration

As already mentioned, the inner boundary of the evolution of the microphysical state of the heliospheric plasma is determined by the corona. Hence it is to be expected that the processes leading to the heating and thus to the acceleration of the solar wind will leave imprints in the velocity distributions functions of solar wind ions. In some scenarios, heavy ion fractionation depends on wave-particle interactions. If a wave resonates with a heavy ion (because of its m/q ratio), it can be selectively heated and hence accelerated.

Measurement Requirements:

- 3-D velocity distribution functions of electrons, protons, and abundant heavy ions.
- Velocity distribution functions of protons and abundant heavy ions, such as O^{5+}, from UV coronagraphic spectroscopy.

Further desirable measurements:

- Composition measurements in solar-wind energy range.

2.1.7 What are the sources and properties of dust in the inner heliosphere, and do Sun-grazing comets contribute to the dust?

Dust in the inner heliosphere can, in principle, stem from three different sources: relic asteroidal or cometary dust that has spiralled in due to the Poynting-Robertson effect; dust as a result of collisions among these particles; dust contributed by sun-grazing comets. Multiple interactions between the dust particles and the solar wind plasma and magnetic field complicate the picture. Far-reaching, dense coronal structures such as streamers, as well as the changing pattern of the near-Sun magnetic field may lead *in-situ* to perturbations of the dust dynamics. A white-light coronagraph measuring both total brightness (B) and polarized brightness (pB) will allow separation of the K- and F-coronae, and will detect the presence of both sun-grazing and other comet populations.

By determining in-situ the distribution, dynamics (and if resources allow, the composition) of dust particles in the near-Sun heliosphere in and out of the ecliptic plane, Solar Orbiter will allow us to investigate the extent of the dust-filled and dust-free zones around the Sun. In doing so, it will deliver crucial data relevant for an understanding of proto-planetary discs and stellar-system formation. It will provide the potential for the discovery of a dust disc that may be fed partly by Sun-grazing comets. Measurements should be carried out continuously during the perihelion passages, and in particular during the high-latitude orbital segments to determine the three-dimensional dust distribution.

Measurement Requirements:

- Mass distribution of dust particles between 10^{-16}g and 10^{-6}g
- White-light coronagraph observations for context.

Further desirable measurements:

- Full chemical analysis and mass resolution of important elements, such as H, C, N, O of carbonaceous material and metals like Na, Mg, Al, Si, Ca and Fe contained in chondritic silicates.

2.1.7.1 What is the role played by the near-Sun dust for the interplanetary pick-up ions?

Interplanetary dust particles near the Sun may originate mostly from comets, but some may also approach the Sun slowly from outside, on time scales of several ten thousand years due to deceleration by the Poynting-Robertson effect. In the vicinity of the Sun, the dust will go through a complicated evolution process, which depends on the particle properties and chemical composition, and which may cause their progressive sublimation as the temperature gets higher. These processes are the source of an additional ion population in the solar wind. Outgassing, sublimation, sputtering and other processes may produce fresh ions and neutrals that can be ionised and then picked up by the solar wind. The study of these pick-up ions will contribute significantly to the understanding of the evolution of interplanetary dust that may provide a prolific inner-heliospheric source of minor solar wind ions in the vicinity of the Sun. It is possible that energetic particles with low charge states are generated by reactions of solar energetic particles with dust surfaces.

Measurement Requirements:

- Mass distribution of dust particles between 10^{-16}g and 10^{-6}g
- White-light coronagraph observations for context.
- Measurements of the most prominent ions (e.g. noble gases, C, N, O, Si, and Fe) in the energy range of a few keV per atomic mass to identify possible pick-ups ions stemming from dust.

2.2 Investigate the Links Between the Solar Surface, Corona and Inner Heliosphere.

There are three characteristic types of large-scale solar corona and wind, prevailing at different heliographic latitude regions of the Sun and heliosphere. The high-speed flow is the basic equilibrium state of the solar wind. Near solar minimum, fast streams emanate steadily from the magnetically open quiet coronal holes around the poles. The low-speed flow originates in a more gusty fashion from and around the equatorial streamer belt and active regions, which are for most of the time magnetically closed. But they may open intermittently and eject magnetic flux and coronal mass, which then leads to a transient and sometimes violent third type of flow, a coronal mass ejection (CME).

The solar magnetic field reveals a rich morphology and many structures. Remnants of these features at all scales are often found as variations of the distant solar wind. Studies of solar features such as active regions, loops, prominences or sunspots are greatly complicated by the fact that their evolution occurs on time scales comparable to the solar rotation period, and is entangled with other effects such as centre-to-limb variation and foreshortening. In order to disentangle such effects it is necessary to observe the Sun in co-rotation.

For the first time, Solar Orbiter will provide such a co-rotational vantage point and unique possibilities for complementary remote-sensing and *in-situ* observations of the Sun from close distances (perihelion of 48 solar radii). Solar rotation will have a negligible influence on the observations during the helio-synchronous orbital phases. Therefore, variability of the Sun's magnetic field and its optical and interplanetary-particles manifestations can be studied extensively for many days at a given heliographic longitude. The favourable vantage points of the Solar Orbiter along the co-rotation trajectory are unattainable by any other means and will allow us to separate spatial from temporal variations.

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

2.2.1 How does the evolution of the solar magnetic field affect the heliosphere at all scales?

SOHO has revealed that the solar magnetic field is highly variable on all scales. This overarching science question addresses the physical consequences of this variability for the heliosphere.

<u>Measurement Requirements:</u>

- Remote sensing of the photospheric magnetic fields strength and structure, and determination of the coronal magnetic structure, using visible light magnetic imaging, EUV imaging of the low corona, and coronagraph observations.
- In-situ measurements of the magnetic field strength and topology of the inner heliosphere.
- EUV spectroscopic observations of the solar atmosphere, and in-situ particle measurements, to measure and compare composition characteristics of the solar wind and its sources.

2.2.2 What are the acceleration and heating mechanisms that lead to coronal hole-associated fast solar wind?

SOHO has provided first measurements of highly non-thermal particle distributions in coronal hole associated wind. Furthermore, there are seemingly contradictory results of temperature measurements by remote and in situ sampling techniques. The related science questions will be answered by a combination of remote sensing measurements and in situ plasma measurements that are expected to show the leftover non-thermal properties from these heating processes. It will be necessary to understand the global context of the in-situ measurements. Note that the appropriate resolutions are driven by the fine-scale structure of the Sun, and in particular a need to get down to fundamental scales within the cell boundaries. The fields of view must be large enough to cover a reasonable number of cells.

Measurement Requirements:

- Solar wind ion charge-state composition measurements.
- Magnetic field measurements of the photosphere, with a capability for 0.5 arcsec pixels, i.e. ~80 km at 0.222 AU, and a large field of view (up to the size of a typical active region, or about 20 arcmin).
- EUV imaging, with 0.5 arcsec pixel size, to determine the structure of the target coronal hole region, and with a field of view capability consistent with the magnetic field observations.
- EUV spectroscopic observations of the same target region, allowing studies of plasma characteristics, such as flows and temperatures, with pixel sizes of 1 arcsec (~160 km at minimum perihelion).

2.2.3 What are the sources of slow solar wind, and what is its temporal and spatial evolution?

There are major unknowns relative to the structure and dynamics of slow solar wind that dominates the Earth space environment. This wind is clearly distinguishable from coronal hole-associated fast wind based on plasma properties, ionic and elemental compositional signatures. The structure of the in situ solar wind suggests source regions of slow wind that may be highly time-variable, or structured on small spatial scales, or both. Several models exist relating slow solar wind to coronal hole boundaries, streamers, or loops. None of these models successfully satisfies both remote and in-situ constraints.

This science question will be answered during the quasi helio-synchronous part of the orbit. For the first time, temporal and spatial variations of the solar wind will be distinguished. It will be necessary to understand the global context of the in situ measurements. Note that here also, the appropriate resolutions are driven by the fine-scale structure of the Sun, and in particular a need to get down to fundamental scales within the cell boundaries. The fields of view must be large enough to cover a reasonable number of cells.

Measurement Requirements:

- Solar wind plasma bulk properties.
- In-situ solar wind ion charge-state composition measurements.
- Magnetic field measurements of the photosphere, with a capability of ~0.5 arcsec pixels (i.e. ~80 km at 0.222 AU) and a large field of view (up to the size of a typical active region, or about 20 arcmin).
- EUV imaging, with 0.5 arcsec pixel size, to determine the structure of the target coronal hole region, and with a field of view capability consistent with the magnetic field observations.
- EUV spectroscopic observations of the same target region, allowing studies of plasma characteristics, such as flows and temperatures, with pixel sizes of 1 arcsec (~160 km at minimum perihelion).

2.2.4 What are the sources and the global dynamics of eruptive events and what are their effects on the inner heliosphere?

Most CME research has focused on CME initiation and prediction. However, there are fundamental problems in our understanding of these CMEs in their evolution in the inner heliosphere. There are indications that these processes are indeed dominant for the majority of space weather effects, including energetic particle acceleration, generation of solar wind and CME plasma. Specific measurements must be carried out to understand the global context of the solar sources. This requires magnetic field measurements, and global EUV data for the structure of the inner corona. Recent results from SOHO indicate that unambiguous detection of CMEs can only be obtained from a coronagraph. This also needs to be addressed with a combination of in-situ and remote-sensing instruments.

Fundamentally, this requires tracing of the magnetic field lines from the IPM back to the Sun (or vice–versa), which can be done by using energetic electrons, which are fast and have small gyro-radii, as field line tracers. Near the Sun these electrons emit bremsstrahlung X-rays, which can be imaged to give the solar source location. These characteristics of the source regions can be studied with EUV and optical imaging and spectroscopic instruments. As the electrons escape along open field lines out into the IPM, they generate solar type III radio bursts that can be detected by radio instrumentation. Then they can be detected in situ by energetic electron detectors to provide unambiguous field line tracing.

Measurement Requirements:

- Solar wind plasma bulk properties.
- In-situ solar wind ion charge-state composition measurements.
- Photospheric magnetic field measurements with modest resolution over the largest field of view possible (equivalent to several tens of heliographic degrees MINIMUM).
- EUV imaging of a large field of view, to study magnetic structure of the CME source region.
- EUV spectroscopy, with modest temporal resolution scanning of the largest field of view possible, to detect signatures of coronal dimming – i.e. of CME source region.
- Coronagraph observations, to identify coronal eruptions in the outer corona.
- Measurements of energetic electrons.
- Radio waves to trace electrons.

2.2.5 What are the solar sources of the solar wind plasma (including that of CMEs), of energetic particles, and the interplanetary magnetic field (IMF)?

To understand the processes leading to the acceleration of the solar wind and of energetic particles, it is essential to identify the source region and determine its characteristics. This can be done by using energetic electrons, which are fast and have small gyro-radii, as field line tracers. Near the Sun these electrons emit bremsstrahlung X-rays that can be imaged to give the solar source location. As the electrons escape along open field lines out into the heliosphere, they generate solar type III radio bursts that can be detected by radio instrumentation. Those electrons that reach the spacecraft will be detected by the in situ instrumentation to provide unambiguous tracing of magnetic field lines from the energetic electron source in the corona to the interplanetary medium. Furthermore, a comparison of the hard X-ray spectra and in situ electron spectra will provide information on the column depth to the source.

If the electron acceleration does not perturb the magnetic topology, such field line tracing will also identify the coronal source region for the solar wind measured at the spacecraft. Recently, the detection of electrons down to energies of <~100 eV streaming out from the Sun in velocity-dispersed events was reported. These events may be the signature of the opening of a closed loop, as hypothesized for the origin of the slow solar wind. Solar Orbiter's near-Sun corotation trajectory provides a unique opportunity to test this. If these events signal the opening of a closed loop, the solar wind ions from that loop should be detected about a day later. Then the characteristics of that solar source region can be determined with the remote sensing instruments.

It is anticipated that the locations and times of these connected observations could be identified on-board so the relevant remote sensing data could be stored for transmission back to the Earth.

Measurement requirements:

- Hard X-ray imaging spectroscopy with moderate spatial resolution and temporal resolution of a few seconds.
- Radio-dynamic spectroscopy from the high corona to the local plasma frequency with few seconds time resolution.
- Electron fluxes from (100 eV to 150 keV) with good spectral, angular, and temporal resolution.
- Bulk solar wind properties.
- Solar wind ion measurements (charge state and composition), time resolution 30 s.
- Magnetograph: Global line-of-sight magnetic field measurements, spatial resolution similar to SOHO-MDI, time-resolution 1 hour.
- Context EUV imaging (whole Sun, spatial resolution of a few arcsec or better, ~1 hour time resolution, cadence of ~10s in burst mode.
- EUV spectroscopic observations with resolution less than the supergranular network, and field of view larger than a number of cells, to provide plasma flow information at a few km/s upwards.
- Coronagraph observations delivering further context information.

2.3 Explore, at all Latitudes, the Energetics, Dynamics and Fine-scale Structure of the Sun's Magnetized Atmosphere.

We wish to understand the basic plasma and radiation processes on the Sun and the evolution of solar magnetic structures on all scales and latitudes in the solar atmosphere. The transition region and inner corona are magnetically structured at scales even below those presently resolvable by SOHO and TRACE, and apparently involve hot and cold plasmas at all temperatures between 10^4 K and 10^7 K. Plasmas widely differing in temperature often co-exist side by side in a hierarchy of filamentary structures, channelled by the magnetic field, which together form the solar atmosphere, consisting of closed loops (flux tubes) and open funnels or streamers and coronal holes.

Given the high spatial resolution due to the spacecraft's proximity to the Sun, combined with high temporal and spectral resolution, and multi-wavelength coverage, the Solar Orbiter will measure the signatures of the basic processes and the elementary structures of the solar atmosphere, providing plasma diagnostic information over the full temperature range existing in the solar atmosphere. This will enable us to understand the dynamics and the mass and energy budget of the solar atmosphere. Solar Orbiter will be used to measure the

- outflows and accelerated particles from magnetic reconnection sites,
- proper motions, line broadenings and Doppler shifts associated with waves,
- properties of coronal waves and loop oscillations, and
- evolution of the elementary magnetic structures.

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

2.3.1 How is the polar high-speed wind generated and how does this relate to the polar plume phenomenon?

Our view of the high-speed wind streams, which emanate from coronal hole regions, is currently extremely limited. Spectral observations, which would be required to determine outflows near the polar region, are only available from the ecliptic plane; thus we are not able to properly identify and characterize outflows at high latitudes. Observations from any latitude above, say, 20 degrees, will provide a unique vantage point for the study of such flows. In addition, the role of the polar plume structure in plasma flows is hotly debated and a proper investigation of such features also demands an out of ecliptic vantage point. The combination of observations at these latitudes with the high-resolution (spatial, spectral and temporal) provided by proximity and advanced instrumentation makes an investigation of these basic features of the polar regions of our star a major target for Solar Orbiter.

Equatorial holes are, of course, frequently observed. They are often confined in size and many observations with SOHO have encountered concerns over line-of-sight integration involving foreground or background features. Solar Orbiter will allow the best view of 'clean' polar region coronal holes. It will also provide opportunities for linking polar 'surface' structure with overlying heliospheric characteristics when the spacecraft flies above the low-latitude extensions of the polar holes.

The basic need is for plasma flow information and imaging to identify the network, plume features and the limb. Other plasma diagnostic information would be useful for a thorough determination of the physical processes. Thus, we require EUV spectroscopy and imaging. We also require magnetic mapping, which has also been very restricted for the polar regions.

Measurement Requirements:

- Instruments pointed to polar coronal hole region.
- EUV spectrometer: $\Delta\lambda$ less than 0.02 Å, i.e. ~ 10 km/s per pixel; FOV > 3 arcmin, i.e. >30,000 km at 0.222 AU (minimum size one network cell) with pixel size 1 arcsec or less; Temporal resolution under 1 minute; Spectral coverage, minimum 4-6 emission lines covering chromospheric to coronal temperatures.
- EUV Imager: FOV > 3 arcmin, pixel size 1 arcsec or less; Co-aligned with spectrometer; Temporal resolution under 1 minute; Minimum of one coronal band, better with one cooler band as well.
- Context white light imaging of the outer corona and, possibly UV imaging and spectroscopy of outer coronal structures.
- Magnetograph: Same FOV and pixel limits as EUV imager; Co-aligned with spectrometer; Temporal resolution under 1 minute.

Note that comparisons of basic structure, evolution, temperatures and flow speeds can be compared to in-situ observations during the passes, for studies of the projection of the quiet Sun atmosphere into the heliosphere above coronal hole regions.

2.3.2 What is the nature of coronal hole boundaries, how do they evolve and how do they project into the inner heliosphere?

The structure and evolution of coronal hole boundaries is fundamental to the evolution of the wider corona. How do coronal holes grow and decay? What processes occur in the boundaries between closed and open field regions? Again, we are limited by the fact that our observations are currently from the ecliptic plane a modest (>20 degree) ascent above the ecliptic will provide a better view of flow patterns in particular, and will provide a better view of polar regions. This will be enhanced significantly by the high resolution due to proximity and advanced instrumentation. There will also be opportunities to over-fly coronal hole boundaries, thus allowing correlated studies of 'surface' features with heliospheric features.

Measurement Requirements:

- In-situ solar-wind plasma composition measurements.
- Instruments pointed to polar boundary region.
- EUV spectrometer: $\Delta\lambda$ less than 0.02 Å, i.e. ~ 10 km/s per pixel; FOV > 5.5 arcmin (>50,000 km at 0.222 AU), with pixel size 1 arcsec; Temporal resolution under a few minutes; Spectral coverage, minimum 4-6 emission lines covering chromospheric to coronal temperatures.
- EUV Imager: FOV > 5.5 arcmin, pixel size 0.5 arcsec; Co-aligned with spectrometer; Temporal resolution under a few minutes; Minimum of one coronal band, better with one cooler band as well.
- Context white light imaging of the outer corona and, possibly UV imaging and spectroscopy of outer coronal structures.
- Magnetograph: Same FOV and pixel limits as EUV imager; Co-aligned with spectrometer; Temporal resolution under a few minutes.

Note that we anticipate comparisons of coronal hole boundary remote sensing plasma observations with overlying in-situ observations when we fly above coronal hole boundaries.

2.3.3 What is the nature of fundamental processes in a stellar atmosphere, including wave activity from source to the corona, the physics of transient events and flux emergence, over all latitudes?

There is a need to understand the most basic processes that occur in a stellar atmosphere. In short, how does energy come from the solar interior and become converted to mass motion or heating by processes in the solar atmosphere. This topic, we divide into three categories:

2.3.3.1 Flux emergence and its consequences

An important phenomenon is the atmospheric reaction to the emergence of new concentrated magnetic flux, such that pores or micro-pores are formed. The high-resolution magnetograms and Dopplergrams will in conjunction with an EUV imager and spectrograph give unprecedented possibilities in understanding the role of small-scale flux emergence in maintaining and regenerating the photospheric field and in energizing the above laying layers.

2.3.3.2 Transient events and the restructuring of the magnetic field

Waves with timescales associated with solar granulation are not the only possible source for chromospheric and coronal heating. Supergranulation dynamics seems to rearrange the chromospheric network, and hence the small scale photospheric field, on roughly 24-hour timescales. This reordering may build up stresses in the overlying coronal field; stresses that only can be relieved as magnetic reconnection attempts to simplify the field geometry. This in turn implies a wide range of small scale phenomena such as blinkers, explosive events and nanoflares and the eventual wave excitations they may generate. These events have been studied extensively using a number of instruments (CDS, EIT, SUMER SXT etc), but never comprehensively by gathering simultaneous information from all relevant atmospheric layers. A thorough understanding of the basic processes signalled by these events needs a co-ordinated high-resolution (temporal, spectral, spatial) effort from a range of latitudes and angles.

2.3.3.3 Wave activity from the photosphere to the corona

Waves will be generated in the photosphere as a natural consequence of granular dynamics: we expect both acoustic and magnetosonic modes as well as Alfvén waves to be excited depending on the detail of the magnetic field topology at the site of excitation. As these modes propagate upwards into the chromosphere the magnetic field will become steadily more important and at the level where the plasma β falls below one – the magnetic canopy – mode conversion will occur. The efficiency of mode conversion and hence the efficiency at which the higher lying layers can be energized by these waves depends crucially on several factors connected to the topology of the field and to the direction and type of modes involved. These factors are at present not understood. An important task for Solar Orbiter is to ascertain the conditions under which wave energy can be injected into the higher lying, low β, regions of the solar atmosphere. This requires the detection of signatures of wave activity, and of the small-scale transient events that trigger these waves in the photosphere.

The lack of simultaneous observations from regions of high β, the canopy and low β at commensurate spatial and temporal resolution has hindered progress. In addition, the ecliptic vantage has so far restricted the view of the polar region and thus inhibited any correlations being made between the behaviour of the large-scale, mainly closed-field, ecliptic regions, and the mainly open-field polar regions. Solar Orbiter will provide the required proximity and range of latitudes/angles.

<u>Measurement Requirements:</u>

- These fundamental process observations require a wide range of spacecraft latitudes, to compare low and high latitude regions, demanding ranges from 0 to many tens of degrees, with instruments pointed to a range of quiet Sun equatorial and polar boundary regions.
- EUV spectrometer: $\Delta\lambda$ less than 0.02 Å, i.e. ~ 10 km/s per pixel; FOV >3 arcmin, i.e. >30,000 km at 0.222 AU; minimum FOV is one cell; pixel size ~1 arcsec; Temporal resolution under one minute; Spectral coverage, minimum 4-6 emission lines covering chromospheric to coronal temperatures.
- EUV Imager: FOV > 3 arcmin to cover at least the area of the spectrometer, pixel size 0.5 arcsec; Co-aligned with spectrometer; Temporal resolution under one minute; Minimum of one coronal band, better with one cooler band as well.
- Context white light imaging of the outer corona and, possibly UV imaging and spectroscopy of outer coronal structures.
- Magnetograph: Same FOV and pixel limits as EUV imager; Co-aligned with spectrometer; Temporal resolution under one minute.

2.4 Probe the Solar Dynamo by Observing the Sun's High-Latitude Field, Flows and Seismic Waves.

The internal structure and dynamics of the near polar regions of the Sun are of paramount importance, and perhaps *the* key to our understanding of the solar activity cycle and solar dynamo. Progress will depend on whether we can directly observe and analyse the differential rotation and meridional flows at higher latitudes and the circumpolar flows near the solar poles. We anticipate that some of the outstanding problems related to the origin of solar magnetism will be solved, since Solar Orbiter will provide the first opportunity for three sets of unique measurements:

- Stereoscopic helioseismology will be possible by combining helioseismic data observed from Earth and from a perspective some 120 degrees away from the Earth as seen from the Sun. Thus rays can be traced that travel through the bottom of the convective envelope and sample the properties of the region within the Sun in which the global dynamo is thought to operate. Once the Solar Orbiter moves away from the ecliptic plane, the ray paths can be studied to increasingly high latitudes, which allows us to measure the properties of the dynamo region and probe the main source region of the Sun's active-region magnetic fields directly.
- Measurements of the flows and field in the Sun's high-latitude and polar regions are of key importance to our understanding of solar activity and internal dynamics. The high-latitude fields are thought to subduct into the convective envelope where they may form the seed field of the next solar cycle. The polar fields also help shape the large-scale corona, and are a dominant contributor to the heliospheric field during much of the solar cycle. On the other hand, the profile with latitude of meridional flow and differential rotation, and the average properties of convective flows (from granules to supergranules) at high latitudes are quantities that are crucial to improving our understanding of the transport of magnetic flux.
- Simultaneous measurements using a range of instruments on board the spacecraft are required to investigate the magnetic connectivity between different layers in the atmosphere, especially after new magnetic flux has erupted out of the convection zone. The possibility of using quasi-simultaneously high-resolution vector-magnetography, EUV spectroscopy and EUV (perhaps also X-Ray) imaging, make this a unique feature of Solar Orbiter that cannot be achieved by any of the other missions planned for the coming 10 years. Understanding the magnetic coupling between photosphere, chromosphere, transition region and corona is one of the key open issues in solar physics.

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

2.4.1 How does the high-latitude field of the Sun evolve on a range of scales?

The Sun's high-latitude field is a mixture of flux that is advected from the main activity belt and flux that emerges locally in ephemeral bipolar regions and the weak pepper-and-salt intra-network field. The small-scale locally-emerging field interacts with the advected large-scale background flux through reconnections. These dynamic interactions likely result in evolving structures in the polar corona, including the polar plumes.

Flux cancellation of the large-scale field patterns occurs predominantly within the polarity-inversion zones that surround the polar cap. These zones are formed by the interaction of the dispersal of flux from the polar reservoirs and the poleward advection of patterns of both polarities, both subjected to the shear of the differential rotation. Polar-crown filaments form within the polarity-inversion zone as helicity and shear are concentrated within a band reaching no higher than 75 degrees in latitude. We believe that it is there that the meridional flow weakens or stops as it is deflected downward. Interestingly, recent results suggest that the differential rotation increases significantly for higher latitudes relative to extrapolations from lower latitudes.

Some dynamo models require field at high latitudes to be retracted back into the Sun in order to act as seed field to the next cycle. As these processes occur close the solar limb as viewed from Earth, the measurement quality is so poor that we cannot at present determine whether flux is retracted into the Sun, or whether it is instead expelled from the Sun.

The study of the evolution of the high-latitude field requires sensitive and accurate magnetograms at moderate resolution to be taken throughout the mission, i.e. also during phases that the Orbiter is far from the Sun. These measurements, combined with measurements from the Earth's perspective, provide the input necessary to compare the measurements global models for its evolution. Because the flux densities at low resolution can be quite low, the magnetograph needs to be very sensitive and precise, with well-calibrated zero points across the detector.

Measurement Requirements:

- Magnetograms with a target resolution of 1 heliocentric degree, taken throughout the mission, providing measurements to the 0.1 Gauss level.

2.4.2 What are the properties of the Sun's surface and subsurface meridional flow and differential rotation at high latitude, and how do these vary with time and position?

The meridional and longitudinal displacement of patterns of magnetic flux at the solar surface has been measured up to a latitude of approximately 70 degrees. Above that, neither the surface differential rotation nor the meridional flow is well known. Establishing whether the poleward advection converges at the rotational pole or away from it, for example, requires observations extending over a few days at a time to track magnetic features or supergranular flow patterns. From the Earth's perspective, patterns cannot be tracked adequately from one rotation to the next because the differential rotation is so strong that patterns are sheared too strongly within that time.

Some measurements of the high-latitude differential rotation have been made from (nearly) the Earth's perspective by measuring global acoustic modes. These modes necessarily average over all longitudes as well as the two hemispheres, so that no detailed 3D maps for the separate hemispheres can be made with this method. Helioseismic studies of the evolving patterns of the subsurface differential rotation at high latitudes require instead imaging of the local modes at these high latitudes as input to local-area seismological inversions. The intensity or velocity signature of these local modes cannot be measured close to the solar limb, as the poles are viewed from Earth, but require a viewpoint well out of the ecliptic, such as offered by the Solar Orbiter.

The combination of surface tracking and helioseismic observations from a vantage point well out of the ecliptic removes both these problems. This will enable us, for the first time, to measure the surface and subsurface flows precisely and unambiguously, and how they connect from the surface to the subsurface flows.

Measurement Requirements:

- Surface flows: Continuum images at 1 min cadence, with resolution of a few arcsec, for periods of order 1 hour for many days during encounter.
- Subsurface flows: Doppler measurements at 1 min cadence and a target of 1 heliospheric degree resolution over a modest area of the polar regions for long periods during the encounters, to detect subsurface flows.

We would like to stress the importance of obtaining measurements during long periods in each orbit, thus permitting long integrations, long-term monitoring, and stereoscopic imaging by combining SO with near-Earth observations.

2.4.3 How do the average properties of granular and supergranular flows depend on latitude?

The Solar Orbiter mission is ideally suited to carry out measurements of collections of granular and supergranular cells to obtain their average properties at high latitudes. Moreover, when observing from a 40-degree latitude, the horizontal flows of supergranules can be measured equally well at the pole as in the equatorial regions. Properties like the average size, peak velocity, interlane width and lifetime of those cells can provide important hints as to the convective transport taking place in high latitudes and allow comparisons with the values obtained in low latitudes. A minimum set of observations can be discerned as follows. Stable statistics for the granules can be obtained with images containing some 10 x 10 cells in them, which can be easily achieved with the planned instrumentation. As for the supergranules, a small number of measurements along a few days can provide the necessary information along the cell lifetime. Finally, a resolution of 0.2" (as measured from Earth) seems to provide enough detail to resolve the granular flows (as shown by comparing the images of the Swedish Solar Tower on the Observatory in La Palma with convection simulations).

Measurement Requirements:

- Granulation: Continuum images of a large field, e.g. 2-3 arcmin, and sub-arcsec pixels, with rapid cadence over long periods, as the spacecraft passes the highest latitude regions.
- Supergranulation: Doppler measurements of supergranular horizontal flows at high latitudes with resolution ~few arcsec over long periods and large fields of view (~2-3 arcmin).

2.4.4 What are the properties of emerging flux at high latitudes?

The high-latitude zones provide an interesting area to study possible turbulent dynamo action in the topmost layers of the Sun's convective envelope. It has been suggested that (part of) the population of ephemeral bipolar regions reflects local dynamo action within the topmost layers of the convective envelope. Study of the population of ephemeral regions at high latitudes may help resolve this issue. Any locally operating dynamo would function within the environment of strong, persistently unipolar fields during most of the solar cycle. Does this affect the properties of the ephemeral regions? Ephemeral regions at low latitudes are oriented almost randomly, but there is a slight preference to be aligned with the large active regions. This suggests a common source for the large and small bipoles, or perhaps an interaction between them within the convective envelope. Is there a preferred orientation for ephemeral regions at high latitudes?

Low cadence observations of magnetograms of a sizable field of view throughout the mission are needed to observe the properties of ephemeral regions at high latitudes around the entire Sun to increase the statistical significance of the derived distributions of sizes, fluxes, orientations, etc.

Measurement Requirements:

- Magnetograms with ~few arcsec resolution over 20 arcmin fields of view, for periods of a full day, at 10 min. cadence, acquired at regular intervals.

The emergence of ephemeral active regions is included within section 2.4.7 and 2.4.8.

2.4.5 How is field removed from the solar surface around the high-latitude polarity inversion regions?

The process of flux cancellation remains a mystery: is flux retracted, expelled, or merely pinched off near the photosphere. Answering this question requires EUV imaging of the corona and optical imaging and magnetometry of the underlying photosphere in order to observe the evolution of the magnetic field in these coupled environments. EUV spectroscopy will probe helpful to constrain the component of motion of loops that occurs perpendicular to the solar surface. These observations should be continuous for a period long enough to significantly exceed the lifetime of ephemeral regions (of order a day) and the lifetime of the typical magnetic flux concentrations (of order a week at maximum polar-cap strength). In order to study the role of the small-scale intrinsically-weak field, observations are needed at higher resolution in space and time, but correspondingly shorter in duration. In order to determine if flux has been expelled from the corona, coronagraph observations are necessary.

Measurement Requirements:

- Low-resolution magnetograms, with ~few arcsec resolution, 20 arcmin field of view, for long periods, at 10 min. cadence, AND
- High-resolution magnetograms, once per minute, 1 arcsec resolution , ~6 arcmin field of view, once per minute, regularly during each phase of highest latitude.
- Coronal EUV imaging at ~few arcsec or better resolution over as large a field of view as possible (up to 20 arcmin), for periods overlapping with the magnetograms at a cadence of approximately 10 minutes.
- Coronal EUV spectroscopy to measure line-of-sight velocities: to cover speeds down to a few km/s.
- White-light imaging (and if possible, UV imaging/spectroscopy) of CMEs.

2.4.6 What are the signatures of the solar dynamo action near the bottom of the convective envelope?

The combined helioseismic observations from the Solar Orbiter and from an observatory near or on the Earth offers the unique and very interesting possibility to carry out stereoscopic seismology by studying both end points of acoustic rays at the surface: whenever the angle between the lines connecting the Sun to the Orbiter and the Earth is approximately 120 degrees, the ray paths of the solar p-modes lead through the bottom of the convective envelope, i.e. the expected seat of the global solar dynamo. Measurement of the Sun's p modes from two such widely separated vantage points is the only way in which the dynamo region can be directly probed. For an orbital inclination of, say, 30 degrees, the highest latitudes to which that region can be probed is about 60 degrees, which encompasses all active latitude and substantially extends the range currently accessible. Such quantitative probing is the only means by which possible changes in the stratification and dynamics of the sites of the strongest fields can be more or less directly probed. No other spacecraft currently planned has this enormous scientific potential.

Measurement Requirements:
See 2.4.2.

2.4.7 What is the evolution of the magnetic field and plasma at different heights from photosphere to corona during the emergence of new magnetic flux in an (ephemeral or normal) active region?

The emergence of flux from the convection zone into the atmosphere is one of the most dramatic processes occurring in the solar surface and atmosphere. State-of-the-art computer experiments are already capable of reproducing this phenomenon between the highest levels of the convection zone and several Mm into the corona. Yet, they still have to use crude assumptions concerning the thermodynamic and radiative transfer properties of the plasma. Even so, they are already displaying fascinating patterns of evolution, including the expansion of the plasma by many orders of magnitude, reconnection of the magnetic field with pre-existing coronal fields, high velocities in transition region and corona, and various others.

The Solar Orbiter mission has the capability of offering coordinated observations of this phenomenon quasi-simultaneously at different levels between photosphere and corona. The Orbiter being an *encounter mission*, it may be best to focus on the emergence of ephemeral active regions, which, at an approximate rate of appearance of 1 per day per (15000 km)^2 are well suited for a pre-programmed operation of the observation. Additionally, studying ephemeral active regions permits extending this observation to high latitudes, given their high rate of emergence at all latitudes.

Measurement Requirements:
See 2.4.8.

2.4.8 What is the topology of the magnetic field in a quiet Sun region at all levels between photosphere and corona and what is the mutual magnetic connectivity between those layers?

Magnetograms taken in the photosphere show a network of magnetic elements in the periphery of the supergranular cells and, according to recent measurements, possibly also quite a substantial amount of magnetic flux in the intranetwork areas. The theoretical study of the mutual connectivity between those elements and of their linkage to the magnetic field in higher levels (chromosphere, corona) has made substantial progress in recent years; yet, there is still a long way to go before solid conclusions can be reached. On the observational side, there is no definitive picture of the extent and structure of the canopy. The coronal structure above supergranules in the quiet Sun is also largely unknown. There is therefore a clear need of observational results for the magnetic structure and linkage in those layers: obtaining them would be a landmark in our understanding of the magnetic structure of the solar atmosphere. Solar Orbiter permits obtaining magnetograms (possibly vector magnetograms) in the photosphere and chromosphere and, through EUV spectroscopy and imaging, temperatures, velocities and the global geometry of the magnetic field in the layers between high chromosphere and corona. If the observations are carried out during the corotation phase, continual monitoring of one supergranule is possible.

Questions 2.4.7 and 2.4.8 can (but need not) be combined into a single series of measurements. By observing a supergranule long enough (say for 2 days) there is a large probability that an ephemeral active region could emerge within the field of view, if the latter is large enough.

Particularly intriguing is the possibility of observing a region somewhere on the disc with Solar Orbiter, while it is in quadrature as seen from Earth, and simultaneously observing the loops above these regions from the Earth, from where they are seen at the limb. The possibility of co-rotating with a particular feature on solar surface is an additional bonus.

Measurement Requirements:

- Photospheric magnetograms: large field of view with high spatial resolution, and target of 1 s integration time per chosen wavelength and spectral resolution of 100 mA. Measurement of the 4 Stokes parameters with 10^{-3} polarization sensitivity, yielding vector B, filling factor and continuum intensity. Cadence of 5 minutes.
- UV/EUV spectrograms: measurement in 6 spectral lines with formation heights covering the range between high chromosphere and corona. High spatial resolution. Typical integration ~5 s.
- EUV imaging of the low corona in at least one wavelength at matching spatial and temporal resolution (at least 1 arcsec pixels and 30 s).

All the above measurements should be repeated along two days in the same position, coinciding with an average lifetime of a supergranule and, also, of the order of the recirculating time of network fields.

Additionally, if a chromospheric line were available:

- chromospheric magnetograms (magnetograms in the visible, supplemented with a chromospheric line filter in a filter wheel): same FOV, spatial and spectral resolution as above; 25 s integration time per chosen wavelength and 2 10^{-4} polarization sensitivity. Same resulting physical quantities and cadence as for the photospheric magnetograms.

The foregoing is the minimum set of measurements necessary to provide an answer to the questions posed in section 2.4. However, if the on-board storage capacity and the telemetry rates could be increased, then it would be highly recommendable to carry out observations with a higher spatial resolution (factor 2) and, for the EUV measurements, a higher cadence of 10 s.

3. PERFORMANCE REQUIREMENTS OF INSTRUMENTATION

3.1 Scientific Priorities

When defining the performance requirements of instrumentation that would be needed to address the scientific questions discussed in chapter 2., the Solar Orbiter Science Definition Team (SDT) considered two options for the payload complement: the Baseline Mission, representing first-class science, while still being compatible with the resource constraints, and a Minimum Mission, representing the minimum payload beyond which the overall science return would become questionable.

3.1.1 Baseline Mission

As noted above, the Baseline Mission represents first-class science, while still being compatible with the constraints imposed by the resources - both technical and financial - that are likely to be available for implementation of the mission. As indicated in sections 3.2 and 3.3 below, the measurements required for the Baseline Mission could be accomplished by an instrument complement comprising the following generic types:

Instrument Type	Measurements
Solar Wind Plasma Package	Solar wind plasma ions and electrons
Fields Package	DC and AC Electromagnetic fields
Particles Package (incl. neutrons, γ-rays and dust) Remote-Sensing Package comprising ♦ Visible light imager & magnetograph ♦ EUV imager ♦ EUV spectrometer ♦ X-ray spectrometer/imager ♦ Coronagraph (white-light, with UV capability if resources allow)	Energetic particles, neutrons, γ-rays, dust Solar images and Doppler velocity and magnetic field; solar disk and corona images; spectroscopy, plasma diagnostics; imaging of acceleration sites, flare timing; coronal imaging and diagnostics

<u>High Priority Augmentations</u>

In the event that appropriate additional resources become available, the SDT recommended a number of so-called High Priority Augmentations to the Solar Orbiter Baseline Mission. These are:

- Higher-resolution remote sensing measurements (e.g., 0.25 arcsec pixels for imaging)
- High-resolution EUV imaging in 3 wavelength bands (the baseline mission foresees a minimum of 1, and preferably 2, wavelength bands)
- Dust particle composition measurements (i.e., chemical analysis and mass resolution of carbonaceous materials like H, C, N, O, noble gases, and metals like Na, Mg, Al, Si, Ca, Fe)
- EUV (He II Lyman-a, 30.4 nm) images of the outer solar corona
- Neutral particle measurements (i.e., energetic neutral atoms in the solar wind / suprathermal velocity range between ~350 and 5000 km/s)
- Coronal radio sounding
- Total solar irradiance measurements

3.1.2 Minimum Mission

In addition to the Solar Orbiter Baseline Mission and the High Priority Augmentations, the SDT also considered a so-called Minimum Mission. While not acceptable as a baseline, a scientifically meaningful mission could be accomplished by an instrument complement comprising the following generic types:

- Solar Wind Plasma Package (as in Baseline)
- Fields Package (as in Baseline)
- Particles Package (limited neutron measurements; no γ-ray measurements; no dust measurements)
- Remote-Sensing Package:
  - Visible light imager / magnetograph and EUV imager (reduced resolution and/or wavelength coverage compared with Baseline)
  - EUV spectrometer (reduced resolution compared with Baseline)
  - Coronagraph (white-light only)

3.2 Performance Requirements of In-situ Instrumentation

This section addresses the measurement requirements on in-situ instruments based on the in-situ science requirements discussed in Chapter 2.1 for the Baseline Mission.

3.2.1 Solar Wind Plasma Package

The solar wind instruments need to measure the solar wind and its velocity distribution function under most conditions, i.e., slow wind, and very fast CMEs and in non-radial flows. The requirements as specified below assume a suite of separate instruments as follows: a proton alpha spectrometer, an electron analyzer system, and a heavy ion spectrometer. The proton alpha spectrometer would measure protons and alpha particles, the electron analyzer system solar wind electrons, and the heavy ion spectrometer solar wind heavy ions and composition.

There are two development drivers, the wide angular coverage required to measure solar wind velocity even in the expected non-radial flow environment and to accommodate the large variation of aberration angle, as well as the high-cadence burst mode required to detect the onset and evolution of plasma instabilities in the solar wind. The detailed requirements are as follows:

Protons and alpha-particles:

- energy range: 200 eV/e to 20 keV/e
- energy resolution: 5% in $\Delta(E/q)/E/q$
- FOV: in ecliptic -45 to +45 degrees toward the Sun direction, ±15 degrees out of ecliptic
- angular resolution: 3 by 3 degrees
- time resolution / cadence capability: 3.0s for entire 3-d velocity distribution function, (moments acceptable as data product)
- Burst-mode capability shall include 0.1s measurements of the 2-d distributions of solar wind protons and alpha particles.

Electrons:

Thermal (core) and super-thermal (halo) electron distributions will be measured with the electron analyzer system. These are needed to study electron dynamics and the kinetic evolution of the solar wind together with observing the heat flux along a given flux tube in order to determine its overall magnetic topology. The electron analyzer system needs to measure the vast majority of 4p steradian with good angular resolution.

- energy range: 1 eV to 5 keV
- energy resolution: 10%
- FOV: 360 degrees (minus 2 x 30 degrees blockage acceptable) in ecliptic by ±45 degrees out-of-ecliptic
- angular resolution 10 by 10 degrees
- time resolution / cadence capability: 3.0 secs, same as the proton alpha spectrometer
- Burst-mode capability: 0.1 sec measurements.

Heavy Ions:
Heavy-ion composition data is required to determine the type and history of a given solar wind speed and to determine the origin of a given solar wind parcel.

- energy range: 0.5 to 100 keV/e in ecliptic, 0.5 to 16 keV out-of ecliptic
- energy resolution: 5% in E/q
- FOV: in ecliptic: -45 to 45 degrees toward Sun direction, out of ecliptic: ±15 degrees
- angular resolution: 6 by 6 degrees
- time resolution / cadence: 5 minutes
- Burst-mode capability: 30 secs.

3.2.2 Fields Package

In addition to the heliospheric magnetic field, both in-situ plasma waves and remote solar radio emissions should be measured. Radio frequency measurements must extend up to 20 MHz, to provide overlap with ground-based solar radio observations of CME and flare phenomena. The following summarizes the required measurements to be acquired by the magnetometer, and radio and plasma wave package:

Magnetic Field:
For the magnetometer the cadence for turbulence investigations is comparable to the proton alpha spectrometer burst mode. The magnetometer burst mode (for kinetic physics) exceeds this by one order of magnitude.

- cadence: 16 vectors / s (normal); 128 vectors / s (burst)
- precision: 1nT absolute
- resolution: few pT
- angular resolution: few degs.

Radio and Plasma Waves:

- 3-axis electric and magnetic remote radio spectra and correlations
  - frequency range: 100 kHz to 20 MHz
- Electric spectra for thermal noise spectroscopy
  - sensitivity: 3 nVvHz
  - frequency range: 10-800 kHz
- Electric and magnetic spectra and waveforms in an internal burst mode (triggered internally, or on input from other instruments and sensors)

- frequency range: near DC to 1 MHz

Burst Mode

Note: The radio plasma wave analyzer or the magnetometer (and energetic particle detector – see 3.2.3) may request burst mode (see section on microstate in science topics) to acquire high-cadence plasma and composition data. Typical time scales in the plasma are the proton gyration period that can be as fast as 0.05 s at 0.2 AU. Typical growth times for the expected instabilities lie in the range of a few gyration periods and hence the proton-alpha-spectrometer burst mode needs to acquire data at a cadence sufficient to detect these microphysical phenomena. In this mode, the proton alpha spectrometer and the heavy ion spectrometer are required to follow the peaks of an ion velocity distribution function at a cadence of 100 ms (proton alpha spectrometer) and 30 s (heavy ion spectrometer). The microphysics of electrons can be measured with the radio and plasma wave analyzer.

3.2.3 Particles Package

The particle package encompasses a comprehensive set of instruments, including multiple sensors for energetic particles, as well as detectors for neutrons, γ-rays and dust particles.

Energetic Particle Detectors:

Measurements of the fluxes, energy spectrum, angular distribution, and composition of energetic ions and electrons from above solar wind energies to >100 MeV/nucleon, with good temporal resolution, are needed. Composition measurements must separate protons, helium, CNO, and Fe as a minimum; ^{3}He must be resolved. Charge-state and elemental/isotopic composition measurements over even a limited energy range are highly desirable. A burst mode is foreseen.

Electrons:
- energy range: ~2 keV to ~1 MeV
- energy resolution: $\Delta E/E$ ~0.2
- Angular resolution/Field of view: ~10 deg over 0-180 deg pitch angle field of view
- time resolution: Normal cadence ~10 s, with burst mode tbd.

Protons:
- energy range: 0.05 to >100 MeV
- energy resolution: $\Delta E/E$ ~0.2
- Angular resolution/Field of view: ~10 deg over 0-180 deg pitch angle field of view
- time resolution: Normal cadence ~10 s, burst mode tbd.

Heavy Ions:
- He – Fe, energy range: 0.02 - 100 MeV/nucleon (species dependent)
- Composition: separate ^{3}He, ^{4}He, CNO group, and Fe as a minimum
- energy resolution: $\Delta E/E$ ~0.2
- Angular resolution/Field of view: ~20 deg over 0-180 deg pitch angle field of view
- time resolution: Normal cadence ~20 s, with <~1 s in burst mode highly desirable

Neutrons and γ-rays

Solar neutrons:

- energy range: ~1 to ~100 MeV
- energy resolution: $\Delta E/E$ ~0.2
- Field of view: Full Sun (minimize material in Sun direction, but presence of heat shielding is acceptable)
- time resolution: Normal cadence ~20 s, with tbd burst mode (during flares)

γ-rays:
- energy range: ~0.3 to 10 MeV
- energy resolution: $\Delta E/E$ ~0.05
- Field of view: Full Sun (minimize material in Sun direction, but presence of heat shielding is acceptable)
- time resolution: Normal cadence ~20 s, with <~1 s in burst mode (during flares)

Dust:
As a minimum, measurements of flux, mass and velocity of dust particles are required.

- Mass range: 10^{-16}g to 10^{-6}g

3.3 Performance Requirements on Remote-Sensing Instrumentation

This section addresses the measurement requirements on remote-sensing instruments based on the solar science requirements discussed in Chapters 2.1 -2.4 for the Baseline Mission.

Concerning imaging and spectroscopy, an observational scenario is foreseen, in which all instruments are co-aligned with a spacecraft optical axis and point together. Offset pointing from the sun-centre will be the result of a pre-planned and agreed joint plan. This is achieved by off-pointing the entire spacecraft.

3.3.1 Extreme -ultraviolet-light imaging and spectroscopy

The scientific requirements for the EUV imager are, through high-resolution imaging, to reveal the fine-scale structure of coronal features, and by taking full-disc images of the Sun, to reveal the global structure of the corona, in particular on the inaccessible "far side" of the Sun and for 0the polar region. These images are required to define the context for spectroscopy and to establish the links between the solar surface and the heliosphere.

High-resolution imaging:
- wavelength coverage: minimum 2 bands

(3 bands preferred spanning the very wide temperature range between a few 10^4 and a few 10^6 K)
- FOV: > 3 arcmin x 3 arcmin
- pixel size: 0.5 arcsec
- < 1 min. cadence

Low-resolution imaging:
- wavelength coverage: 1 band (cool/hot TBD)
- FOV: > 5.2 deg x 5.2 deg
- pixel size > 9 arcsec
- < 1 min cadence

It is a commonly held viewpoint that true quantitative diagnostics depend on the provision of sophisticated spectroscopic techniques, capable of exploiting our knowledge of the underlying basic atomic physics. This is a valid statement but the performance requirements for Solar Orbiter mission have to be modest. Solar plasma diagnostics is provided by the analysis of a few selected spectral windows with lines coming from ions at different ionization stages, and thus from different temperature regions. The spectroscopic technique involves using the line profiles, giving via radiance a measure of ion density, and the line shifts in order to derive by the Doppler method values for the ion kinetic temperature and bulk material flow velocity.

Such measurements concern an area of prime science for the Solar Orbiter mission. The emphasis will be on the observation of a few bands only. The chosen wavelength range ideally should include strong upper-chromosphere, transition-region and coronal lines. Strongly suggested wavelength bands are: 170-220 Å, 580-630 Å and 912+ Å. The science requirement is for a set of bands with access to many emission lines, possibly 30-50 or even more. Individual observational sequences would typically make use of 4-6 selected lines, where the selection will depend on the study and is required to be flexible. The EUV is crowded, so modest wavelength coverage can fulfil the science requirements.

Spectroscopy:

- spectral coverage: selected bands to cover emission line selections appropriate to the solar atmosphere (e.g., 170-220 Å, 580-630 Å and 912+ Å)
- spectral resolution: $\Delta\lambda = 0.02$Å
- FOV: > 3 arcmin x 1 arcsec (for 1 measurement with spectral information)
- FOV: > 3 arcmin x 3 arcmin (for rastered images and spectral information)
- pixel size: 1 arcsec
- < 1 min. cadence

3.3.2 Visible-light imaging and polarimetry

Still today, the main way to get information on the coronal magnetic field is by numerical extrapolation that uses the photospheric field as a boundary condition. Potential and linear force-free extrapolations have been used to a point where it is clear that a better description is needed. Such sophisticated non-linear force-free or even full MHD codes (which include the effects of the gas pressure distribution at the photosphere) are already available. These methods have one key point in common: they make use of the vector magnetic field and are simply not applicable if only the longitudinal (or B_{LOS} or even B_z) component is known.

Consequently, for Solar Orbiter vector magnetic field measurements are required, which render it possible to analyse solar magnetic activity and to establish the links between the Suns's surface and the corona, respectively, the heliosphere, a capability that is considered to be a fundamental trait and indispensable virtue of this mission. Additionally, the measurement of the vector magnetic field allows us to infer the magnetic helicity, a quantity of extreme importance in understanding the solar source and magnetic nature of CMEs.

The stated science objectives lead to the following requirements on the measurements:

General:

- Field of view: > 15 arcmin (High Resolution); > 150 arcmin (Low Resolution)
- Pixel size: 0.5 arcsec (High Resolution), ~ few arcsec (Low Resolution)
- < 1 min. cadence
- Lower cadence modes available

Magnetograms:

- Dynamic range: 3.5 kG
- S/N (longitudinal) per pixel: 10^3 in 30 seconds and per pixel (< 10 G precision).
- S/N (transverse) per pixel: 10^3 in 30 seconds and per pixel (< 200 G precision).
- Accuracy: 0.1 G (longitudinal), 2 G (transverse)

Doppler measurements:

- Dynamic range: > 47 km/s (spacecraft plus solar rotation)
- Precision: 15 m/s per pixel

Imaging (Continuum):

- Dynamic range: 10^3 per pixel
- Precision: <0.5 % (flat-field uniformity) per pixel

3.3.3 Coronagraphy

The orbit profile will take Solar Orbiter through the inner heliosphere and outer corona. A white-light coronagraph instrument, therefore, will be indispensable in providing the context observations for the entire mission payload, in general, and the *in-situ* measurements, in particular by providing unambiguous detection of CMEs and of comets. A UV channel could possibly be included, giving enhanced performance.

A coronagraph employing a combination of classical broad-bandpass, polarized imaging of the visible-light K-corona, and if resources allow, narrow-bandpass imaging of the corona in the HI Lyman-α, would therefore result in the knowledge of the density distribution and kinematics of the major components of the coronal plasma, that is, electrons and hydrogen.

Polarized visible-light imaging:

- Field of view (spacecraft at 0.222 AU): ~1.2 to 3.5 solar radii. Extendable to 3 to 15 solar radii with adjustable pointing
- Spectral coverage: 450-650 nm
- Stray-light rejection: 10^{-11} $B/B_{\odot}$
- Pixel size: < 8 arcsec
- Dynamic range: $\geq 10^4$
- Polarization sensitivity: < 1 %
- Polarization S/N: > 10^4
- Cadence: 5 min. (CMEs obs.); 10 min. (synoptic)

UV imaging (optional if resources allow):

- FOV (spacecraft at 0.222 AU): ~1.2 to 3.5 solar radii. Extendable to 3 to 10 solar radii with adjustable pointing
- Spectral coverage: HI Lyman-α, (121.6 ± 5) nm
- Stray-light rejection: 10^{-5} $B/B_{\odot}$
- Pixel size: < 8 arcsec
- S/N: > 10
- Cadence: < 15 min.

UV spectroscopy (optional if resources allow, simultaneously combined with imaging):

- FOV (spacecraft at 0.222 AU): ~1.2 to 3.5 solar radii. Extendable to 3 to 10 solar radii with adjustable pointing
- Spectral coverage: HI Lyman-α, 121.6 nm; OVI 103.2/103.7 nm
- Minimum most probable (e^{-1}) particle speed: 30 km/s ($\Delta\lambda/\lambda \leq 10^{-4}$)
- Minimum line-of-sight velocity: 30 km/s
- Stray-light rejection: 10^{-5} $B/B_{\odot}$
- Pixel size: < 8 arcsec
- S/N: > 10 (line profile); > 10^2 (integrated profile)
- Cadence: 30 min.

3.3.4 Hard X-ray imaging/spectroscopy

The scientific requirements discussed in Chapter 2 lead to the following instrument performance requirements for X-ray imaging and spectroscopy:

- Energy range: 3 to 150 keV
- Spectral resolution: 2 to 4 keV FWHM
- Field of view for imaging: 24 arcmin (~230,000 km at 0.222 AU)
- Angular Resolution: 2.5 arcsec resolution (~400 km at 0.222 AU)
- Field of view for source centroid location: Full Sun at 0.222 AU, i.e. ~150 arcmin.
- Time resolution: Basic cadence: 8 Hz, post facto on-board data selection/averaging, actual time resolution based on count rates

3.4 Coordinated In-situ / Remote-sensing Observations:

In addition to regular data acquisition controlled by the individual instruments, a data acquisition mode is envisaged whereby automated acquisition of remote-sensing data (especially data from the EUV imager and X-ray imager) can be triggered by one or more instruments of the in-situ packages. This will require the instruments to have an external trigger capability.