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DOCUMENT

Solar Orbiter Science Requirements Document

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1 SCOPE

This document replaces the original Solar Orbiter Science Requirements Document (SCI-SH/2005/100/RGM, dated 31 March 2005) that was prepared by the Solar Orbiter Science Definition Team and was included in the Proposal Information Package for the ESA Announcement of Opportunity for the Solar Orbiter Payload issued on 18 October 2007. The present document is based on the Solar Orbiter Assessment Study Report (ESA/SRE/(2009)5) and includes information relevant to the payload instruments selected via the ESA AO and the NASA Focused Opportunity for Solar Orbiter, as well as the modified mission profile that was introduced during the course of the ESA Cosmic Vision 2015-2025 down-selection process in early 2010. As in the original document, 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 quantification of the scientific measurements is given. This is followed by a summary of the selected payload, a brief description of science operations coordination and science planning, and a discussion of supporting observations and theory/modeling efforts.

2 INTRODUCTION

Solar Orbiter's mission is to address the central question of heliophysics: ***How does the Sun create and control the heliosphere?*** This, in turn, is a fundamental part of the second science question of ESA's Cosmic Vision programme: ***"How does the solar system work?"*** Solar Orbiter is specifically designed to identify the origins and causes of the solar wind, the heliospheric magnetic field, solar energetic particles, transient interplanetary disturbances, and the Sun's magnetic field itself.

The supersonic solar wind, driven by dynamic plasma and magnetic processes at the Sun's surface, expands to surround the solar system's planets and the space far beyond. Below the surface, the solar dynamo drives magnetic fields whose buoyancy brings them to the surface where they form huge arcades of loops, which contain enormous amounts of stored energy. These magnetic loops are stretched and sheared by the Sun's differential rotation and unknown surface processes, eventually erupting in explosions, which eject magnetic structures that fly into the solar system, occasionally impacting the Earth and its magnetic shield with disruptive effects on space and terrestrial systems. Understanding the complex physical processes at work in this system is the central goal of heliophysics. Since the Sun and presumably the heliosphere are typical of many small stars and their stellar spheres, these studies are relevant to astrophysics, but are unique since the Sun alone is close enough for detailed study.

Over the past ~15 years, an international effort to understand the Sun and heliosphere has been undertaken with an array of spacecraft carrying out both remote observations at visible, UV, and X-ray wavelengths, as well as in-situ observations of interplanetary plasmas, particles, and fields. Combined and coordinated observations from missions such as Ulysses, Yohkoh, SOHO, TRACE, RHESSI, Hinode and STEREO have resulted in an enormous advance in our understanding of the Sun and heliosphere, and have proven that critical progress in understanding the physics requires both remote and in-situ observations working together.

Although our vantage point at 1 AU is close by astrophysical measures, it has been long known that much of the crucial physics in the formation and activity of the heliosphere takes place much closer to the Sun, and that by the time magnetic structures, shocks, energetic particles and solar wind pass by Earth they have already evolved and in many cases mixed so as to blur the signatures of their origin. With the proven effectiveness of combined remote and in-situ studies on the missions cited above, it is clear that ***the critical new advances will be achieved by flying a spacecraft combining remote and in-situ observations*** into the inner solar system. From this inner-heliospheric vantage point, solar sources can be identified and studied accurately and combined with in-situ observations of solar wind, shocks, energetic particles, etc., before they evolve significantly. The expertise gained by the international scientific community on existing missions has been used to design Solar Orbiter to provide the complete set of required measurements.

This document outlines the major physical problems that Solar Orbiter will address and how Solar Orbiter will address them.

3 SOLAR ORBITER'S TOP LEVEL SCIENCE OBJECTIVES

Solar orbiter's scientific mission can be broken down into four top-level science objectives:

1. How and where do the solar wind plasma and magnetic field originate in the corona?

The solar corona continuously expands and develops into a supersonic wind that extends outward, interacting with itself and with the Earth and other planets, to the heliopause boundary with interstellar space, far beyond Pluto's orbit. The solar wind has profound effects on planetary environments and on the planets themselves – for example, it is responsible for many of the phenomena in Earth's magnetosphere and is thought to have played a role in the evolution of Venus and Mars through the erosion of their upper atmospheres.

Two classes of solar wind – 'fast' and 'slow' – fill the heliosphere, and the balance between them is modulated by the 11-year solar cycle. The fast solar wind (~700km/s and comparatively steady) is known to arise from coronal holes. The slow solar wind (~400 km/s) permeates the plane of the ecliptic during most of the solar cycle so it is important to Earth's space environment. The slow solar wind differs from the fast wind in mass flux and composition, which is consistent with confined plasma in the solar corona. The specific escape mechanism through the largely closed magnetic field is not known since candidate sites and mechanisms cannot be resolved from 1 AU. Fast and slow wind carry embedded turbulent fluctuations, and these also display different properties compatible with different solar origins. It is thought that such fluctuations may be responsible for the difference in heating and acceleration between different solar wind streams.

Understanding the physics relating the plasma at the solar surface and the heating and acceleration of the escaping solar wind is crucial to understanding both the effects of the Sun on the heliosphere and how stars in general lose mass and angular momentum to stellar winds.

2. How do solar transients drive heliospheric variability?

The largest transient events from the Sun are coronal mass ejections (CMEs), large structures of magnetic field and material that are ejected from the Sun at speeds up to 3000 km/s. CMEs are also of astrophysical interest since they are the dominant way that stars shed both magnetic flux and magnetic helicity that build up as a result of the stellar dynamo. Interplanetary CMEs (ICMEs) are the major cause of interplanetary shocks, but the locations and mechanisms by which shocks form around them are not known since they occur in the inner solar system. Similarly, the longitudinal structure of ICMEs is not directly observable from the ecliptic, while their extent has a large impact on the acceleration of energetic particles. ICMEs are a major cause of geomagnetic storms but their effectiveness at disrupting the magnetosphere is only loosely related to the parent CME, because the evolution of the propagating cloud with the surrounding heliosphere is complex and has not been well studied. These unknowns have direct impact on our ability to predict transient ("space weather") events that affect Earth.

3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?

Like many astrophysical systems, the Sun is an effective particle accelerator. Large solar energetic particle (SEP) events produce highly energetic particles that fill the solar system with ionizing radiation. CME-driven shocks can produce relativistic particles on time scales of minutes, and many CMEs convert ~10% of their kinetic energy into energetic particles. Other processes produce high-energy particles on magnetic loops without involving shocks. The multiple processes operating in

SEP events are not well understood or distinguishable from observations at 1 AU. In particular, particles accelerated in the corona and inner heliosphere are scattered by inhomogeneities in the interplanetary magnetic field (IMF) before they arrive at Earth, destroying much of the information they carry about the processes that accelerated them. Particle transport and scattering in the inner solar system are poorly understood since the turbulence properties cannot be determined from 1 AU. The actual seed population of particles energized by CME-driven shocks in the inner solar system is unexplored, and needs to be understood to construct a complete picture of particle acceleration in shock-related events.

4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

The Sun's magnetic field connects the interior of the star to interplanetary space and is dominated by a quasi-periodic 11-year sunspot cycle that modulates the form of the heliosphere and strongly affects the space environment throughout the solar system. The large-scale solar field is generated in the Sun's interior, within the convection zone, by a dynamo driven by complex three-dimensional mass flows that transport and process magnetic flux. Despite notable advances in our knowledge and understanding of solar magnetism made possible by Ulysses, SOHO, and Hinode observations as well as by recent theoretical models and numerical simulations, fundamental questions remain about the operation of the solar dynamo and the cyclic nature of solar magnetic activity. Of paramount importance to answering these questions is detailed knowledge of the transport of flux at high latitudes and the properties of the polar magnetic field. To date, however, the solar high latitudes remain poorly known owing to our dependence on observations made from the ecliptic. In addition to questions about the global dynamo and the generation of the large-scale field, there are unanswered questions about the origin of the small-scale internetwork field observed in the quiet photosphere. Is this weak field produced by turbulent local dynamo action near the solar surface?

4 SCIENCE REQUIREMENTS

This chapter describes how the Solar Orbiter science investigation will be implemented and places special emphasis on demonstrating traceability: the flow-down from the science objectives discussed in the previous section to the observations and measurements required to meet those objectives, to the instrumentation needed to provide the required measurements, and to the requirements placed by the science objectives on the design of the orbit. Table 4.1 - Table 4.4 map the science questions to the required observations and instrumentation. Table 4.5 then traces in detail the flow-down from observations to specific measurement requirements to the capabilities of the selected payload. Table 4.6 provides an overview of the payload. (For more detailed information on the payload, see the Solar Orbiter EID-Bs.)

4.1 Observations, Measurements, and Orbital Characteristics

To address its science objectives, Solar Orbiter will use a combination of in-situ and remote-sensing instrumentation, a unique orbit and mission design, and a well-planned observational strategy to explore systematically the region where the solar wind is relatively unevolved and heliospheric structures are formed.

As discussed in Section 3, the broad question that defines the overarching objective of the Solar Orbiter mission is broken down into four interrelated scientific questions. Common to all of these questions is the requirement that Solar Orbiter make in-situ measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun that they are still relatively pristine and have not had their properties modified by dynamical evolution during their propagation. Solar Orbiter must also relate these in-situ measurements back to their source regions and structures on the Sun through simultaneous, high-resolution imaging and spectroscopic observations both in and out of the ecliptic plane.

4.1.1 Measurement Requirements and Instrument Capabilities

The measurement requirements for Solar Orbiter have been defined by two independent science definition teams. The Solar Orbiter Science Definition Team provided the input for the original Solar Orbiter Science Requirements Document (SCI-SH/2005/100/RGM) taking into account the Payload Definition Document and the reports from the Payload Working Groups. The Joint ESA-NASA Heliospheric Explorers (HELEX) Science and Technology Definition Team subsequently refined Solar Orbiter's observation and measurement requirements in the context of the joint HELEX mission (then comprising Solar Orbiter and NASA's Solar Sentinels). These formed the basis for the competitive AO and the initial instrument selection and have subsequently been revised based on instrument selection and the increased minimal perihelion distance.

Table 4.1 - Table 4.4 specify the observations required to address Solar Orbiter's science objectives and the specific science questions. Table 4.5 maps these required observations the suite of instruments that constitute the Solar Orbiter payload. This table repeats the required observations in its first column and maps them to instruments and measurements in its second column. The third column gives detailed measurement requirements for each of the observations, and fourth column gives the corresponding capability of the selected instrument.

4.1.2 Orbit Requirements

The science objectives discussed in Section 3 specifically identify a set of orbit characteristics and mission design parameters that define the Solar Orbiter mission. In summary, the requirements on the orbit are to:

1. Go close to the Sun (within 0.3 AU);
2. Have periods in which the relative angular motion of the spacecraft with respect to the solar surface is such that individual solar surface features can be tracked for periods approaching one solar rotation (i.e., significantly longer than from Earth orbit);
3. Achieve moderate out-of-ecliptic viewing (~25°) and latitudinal coverage; and
4. Comprehensively characterize conditions in the inner heliosphere as a function of distance and latitude. One critical factor that drives the mission and spacecraft design is the perihelion distance, while a second is the trade between perihelion distance and relative motion with respect to the solar surface; and a third is inclination of the orbit. The detailed scientific rationale for these requirements is reviewed below.

Perihelion Distance Requirement. The Helios mission, which reached a perihelion distance of 0.29 AU, demonstrated that stream-stream interactions, solar wind acceleration and wave-particle interactions are still active at this distance. In order to measure the less processed, pristine solar wind streams and the ongoing interaction at their interfaces as well as the kinetic processes that accelerate and heat the wind, Solar Orbiter must spend sufficient time within 0.3 AU in order to guarantee multiple observations of the fast-slow stream interface.

Another driver to go close to the Sun is the measurement of energetic particles, which should be made within one or two scattering mean free paths (typically 0.2 AU) of their source in order to minimize propagation effects. Solar Orbiter therefore must spend several solar rotations, sufficient to pass over several active regions, while within 0.4 AU.

The maximum time a particular location on the Sun can be tracked by the spacecraft is intimately linked, through orbital mechanics, with Solar Orbiter's perihelion distance. The main drivers are the need to observe solar features or source regions, while at the same time sampling in situ the solar wind and energetic particles emanating from them on time scales that are comparable to their growth and evolution. From Earth orbit, no region can be observed for more than ~14 days, observations being further restricted by line-of-sight effects when the regions are near the solar limb. In order to determine the evolution of solar features, Solar Orbiter must travel sufficiently slowly above the solar surface to observe a feature within ±30° of the disk centre for a time that is comparable to active region growth times (~10 days). Furthermore, Solar Orbiter must also maintain an uninterrupted view of solar features for a time comparable to the total lifetime of a small active region (~27 days).

Latitude Requirement. The principal driver for attaining an out-of-ecliptic vantage point is to resolve outstanding questions about the dynamics of the solar dynamo and to measure directly the fast/slow solar wind boundary emanating from the edges of high latitude coronal holes. The inclination of the heliospheric current sheet means that this boundary must be sampled at a range of latitudes, comparable to the current sheet's inclination, resulting in a requirement to measure from ±15° solar latitude within 0.5 AU. In order to accurately measure the polar magnetic field and its dynamics and meridional transport, at least five consecutive days of observations above 25° are required.

Comprehensive Characterization of the Inner Heliosphere. Many of Solar Orbiter's science objectives require a comprehensive characterization of the properties of the inner heliosphere at a level of sophistication never previously achieved. The only other mission to explore the inner heliosphere between 0.3 and 1 AU, Helios, had a payload limited in many ways (measurements, cadence) compared to modern instrumentation and lacked several critical elements such as remote sensing (imaging and spectroscopy) observations and composition measurements. Helios was also restricted to measurements in the ecliptic plane. Solar Orbiter will make critical, previously unavailable measurements that are essential to fully characterize the inner heliosphere and relate these properties out to near-Earth measurements at 1 AU.

4.1.3 Summary of Requirements on the Solar Orbiter Spacecraft

The scientific measurement requirements detailed above place the following requirements on the spacecraft:

- Solar Orbiter must be a three-axis stabilized spacecraft with a pointing accuracy sufficient to achieve the scientific objectives.
- Solar Orbiter must satisfy electromagnetic cleanliness requirements such that the magnetometer and radio and plasma waves instruments can accurately measure relevant physical parameters and electrostatic cleanliness requirements so as not to significantly compromise the plasma measurements.
- Solar Orbiter must satisfy particulate and silicate cleanliness levels such that the EUV and white light instruments can measure relevant physical parameters.
- For each operational orbit, the Solar Orbiter spacecraft must allow full operations of the complete payload for a minimum of three continuous periods of 10 days each.

4.2 Selected Payload Summary

The Solar Orbiter payload was selected from proposals submitted in response to the ESA Announcement of Opportunity (AO) for the Solar Orbiter Payload, released on 18 September 2007, and to the NASA Small Explorer Focused Opportunity for Solar Orbiter (SMEX/FOSO) AO, released on 22 October 2007). Following a review of the 14 proposals submitted to ESA, the Payload Review Committee (PRC) issued a final report on 24 May 2008 recommending a payload for selection. ESA subsequently called for an independent review of the PRC's recommended payload in the context of a joint scientific programme with NASA's high-priority Solar Probe Plus (SPP) mission.[1] The joint ESA-NASA review panel confirmed the validity of the recommended payload in its report of March

[1]The PRC's original payload recommendation was made in the context of the HELEX programme, a joint ESA-NASA programme involving both Solar Orbiter and the NASA Sentinels mission. During the course of 2008, however, NASA assigned higher priority to a re-designed Solar Probe mission, Solar Probe Plus (SPP), which is planned to be operating at the same time as Solar Orbiter and whose science objectives are strongly synergistic with those of Solar Orbiter (cf. §3.4.1).

2009. As a result, the instrument selections as recommended by the PRC in 2008 were formally announced on 20 March 2009 (selection to be confirmed after mission approval). In parallel, NASA announced the results of the FOSO selection, and selected 2 instruments and portions of 2 instruments to be included in the Solar Orbiter payload. The payload consists of the following instruments:

The in-situ instruments:

- The Solar Wind Analyser instrument suite (SWA, PI: C. J. Owen, UK) will fully characterize the major constituents of the solar wind plasma (protons, alpha particles, electrons, heavy ions) between 0.29 and 1.4 AU.
- The Energetic Particle Detector experiment (EPD, PI: J. R. Pacheco, Spain) will measure the properties of suprathermal ions and energetic particles in the energy range of a few keV/n to relativistic electrons and high-energy ions (100 MeV/n protons, 200 MeV/n heavy ions).
- The Magnetometer experiment (MAG, PI: T. S. Horbury, UK) will provide detailed in-situ measurements of the heliospheric magnetic field.
- The Radio and Plasma Waves experiment (RPW, PI: M. Maksimovic, France) will measure magnetic and electric fields at high time resolution and determine the characteristics of electromagnetic and electrostatic waves in the solar wind from almost DC to 20 MHz.

The remote-sensing instruments:

- The Polarimetric and Helioseismic Imager (PHI, PI: S. K. Solanki, Germany) will provide high-resolution and full-disk measurements of the photospheric vector magnetic field and line-of-sight velocity as well as the continuum intensity in the visible wavelength range.
- The Extreme Ultraviolet Imager (EUI, PI: P. Rochus, Belgium) will provide image sequences of the solar atmospheric layers from the photosphere into the corona.
- The Spectral Imaging of the Coronal Environment EUV Spectrograph (SPICE, PI: D. M. Hassler, USA) will provide spectral imaging of both the solar disk and in the corona to remotely characterize plasma properties of regions at and near the Sun.
- The Spectrometer/Telescope for Imaging X-rays (STIX, PI: A. O. Benz, Switzerland) provides imaging spectroscopy of solar thermal and non-thermal X-ray emission from ~4 to 150 keV.
- The Multi Element Telescope for Imaging and Spectroscopy Coronagraph (METIS/COR, PI: E. Antonucci, Italy) will perform broad-band and polarized imaging of the visible K-corona, narrow-band imaging of the UV and EUV corona, and UV and EUV spectroscopy in a coronal sector of 32° width.
- The Solar Orbiter Heliospheric Imager (SoloHI, PI: R. A. Howard, USA) will image both the quasi-steady flow and transient disturbances in the solar wind over a wide field of view by observing visible sunlight scattered by solar wind electrons.

Figure 4.1 illustrates the accommodation of the instruments on the spacecraft. An overview of the selected payload is given in Table 4.6. Complete, detailed information about the selected payload can be found in the individual EID-Bs for each instrument.

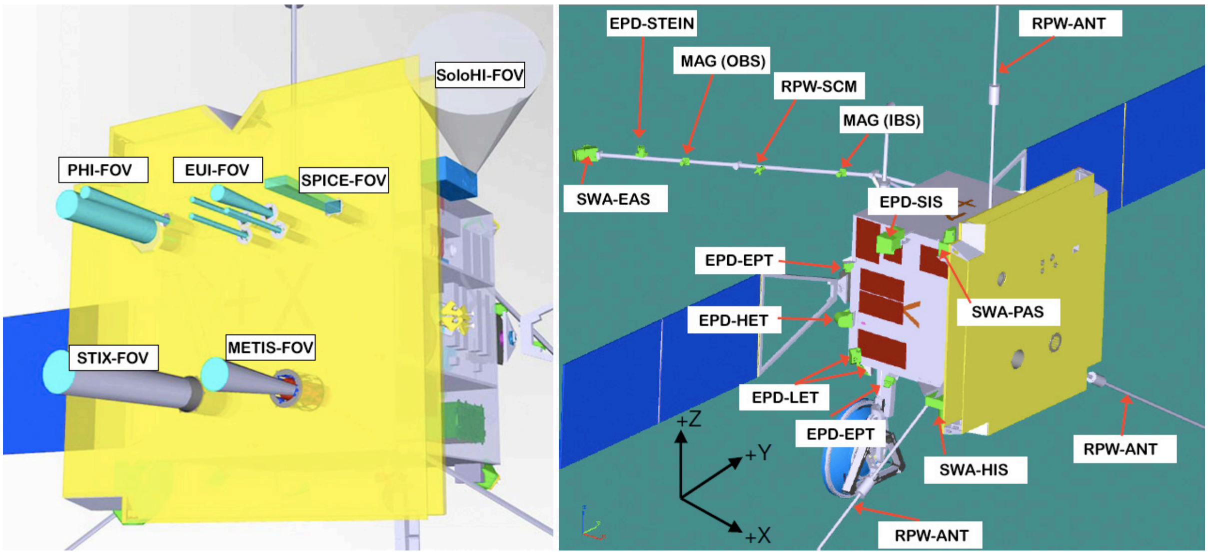

Figure 4.1 Illustrations of the preliminary accommodation of Solar Orbiter's remote-sensing instruments (left) and in-situ instruments (right) [to be updated].

4.3 Science Operations Coordination and Science Planning

The science return of the Solar Orbiter mission will be maximized by coordinating operations and data taking between instruments. Every science objective described in Section 2 requires coordinated observations between several in-situ and remote sensing instruments, and the strength of the Solar Orbiter mission stems from the synergy and comparative analysis of in-situ and remote sensing observations.

Since the orbits of Solar Orbiter evolve significantly from one to the next and so do the designated encounter periods in which Solar Orbiter will be out of contact with Earth, detailed planning will be required for every science orbit by the SWT/SOC. This endeavour will be very similar to what has been used in a highly successful manner in ESA's SOHO missions Joint Observation Programmes.

4.3.1 Data Rates, Telemetry, Inter-Instrument Communication & Burst Mode

Given the flexibility of the on-board SpaceWire bus, instruments can communicate with each other, making it possible for teams to coordinate operations without incurring additional workload for the spacecraft operations team.

Since the telemetry rates from Solar Orbiter are limited, the spacecraft will be equipped with a large mass memory to allow for variable downlink speeds. However, the instruments are not limited to taking data at one rate and a number of coordinated and targeted data rate selection mechanisms will be implemented.

Burst Mode. Coordinated burst-mode data acquisition will enable detailed studies of the microphysics of the solar wind. Approximately 10% of the data return is expected to be in burst mode, with around 10 times the data rate of normal mode, corresponding to around 1% of the time. For instance, this mode will be used to study solar flares, which explosively release magnetic energy, driving shocks and accelerating particles. The Solar Orbiter X-ray instrument (STIX) will detect the flare's onset and location and trigger high time resolution measurements by remote sensing instruments to determine the properties of the flare site and its evolution, as well as Solar Orbiter's Radio and Plasma Wave instrument (RPW) to measure radio emission from accelerated particles and its Energetic Particle Detector (EPD) to measure accelerated particles passing the spacecraft. Burst mode will also be used to study shocks crossing the spacecraft. They will be detected in the magnetic field and plasma and will trigger short burst mode measurements by Solar Orbiter's in-situ suites

(MAG, RPW, SWA, and EPD) to quantify shock substructure and the motion and acceleration of particles nearby. Rolling buffers within the instruments will make it possible to store high-cadence data from upstream of the shock trigger time.

Small-scale kinetic processes will be measured using coordinated burst mode measurements of the magnetic and electric fields and particle distributions by Solar Orbiter's MAG, RPW and SWA. By sharing data on local plasma and field conditions, the instruments will trigger short burst mode intervals to ensure a wide coverage of different plasma regimes. In addition, some remote sensing instruments will take high cadence measurements of sub-fields of view. These can be planned based on known positions of active regions, but also in response to triggers based on emission levels of rapid changes in observed conditions.

Sharing of Magnetic Field Direction. Magnetic field directions can be shared among the in-situ instruments to produce reduced velocity distribution functions on board Solar Orbiter, thus greatly reducing the telemetry requirements. The local magnetic field direction is important to particle instruments in order to compute reduced data products such as temperature anisotropies or pitch-angle distributions. The Solar Orbiter magnetometer will transmit the measured magnetic field direction in real time to other instruments via the SpaceWire bus. The generation of high time-resolution data and accurately reduced distribution functions requires precise timing knowledge between the contributing instruments, which will be achieved by synchronizing instrument clocks with the spacecraft via the SpaceWire bus. An accuracy of around 10ms can be achieved and will be used to ensure synchronization of sampling between instruments. This is sufficient given the proton gyro-period of roughly half a second at ~65 solar radii (near perihelion).

4.3.2 Science Orbits

Certain subsections of every ~150/168-day (depending on resonance condition) orbit are designated as part of the 'encounter period.' This typically consists of a 10-day window centered on the perihelion for high-resolution imaging studies and two 10-day windows centered on the highest latitudinal extents reached during that specific orbit or maximum co-rotation. If operational constraints allow, other encounter windows may be considered in order to optimise the use of resources (e.g. telemetry) and increase the science return. In-situ instruments operate during the entire orbit whereas the remote-sensing instruments operate primarily during the 30 days within the encounter windows.

4.4 Supporting Observations

4.4.1 Space-Based Observations Supporting Solar Orbiter Science

Solar Probe Plus (status October 2010). The NASA Solar Probe Plus mission is highly complementary to Solar Orbiter. Solar Probe Plus is a ~7 year mission to approach the Sun, planned to be launched in 2018 and reaching a 9.5 R_s x 0.7 AU orbit with an 88-day period resulting in many close passes to the Sun. Since Solar Probe Plus' scientific payload, selected in September 2010, will contain primarily in-situ instruments and a single Heliospheric Imager, the two missions can address many questions in powerful new ways. Figure 4.2 shows cases of particular interest, which occur during nominal missions: The left panel shows the case of SPP and Solar Orbiter radially aligned. In this configuration the radial evolution of solar wind properties, including shock and turbulence properties can be studied directly. The middle panel shows cases of alignment along a nominal IMF spiral, where energetic particles travelling past one of the two spacecraft will later move past the other, permitting direct tests of energetic particle transport and scattering since the source function is determined at one of the spacecraft and result is seen at the other. The right panel shows cases of quadrature alignment, where Solar Orbiter remotely observes plasma low in the corona that later passes by Solar Probe Plus, allowing tests of radial evolution of solar wind plasma, shocks, and other structures.

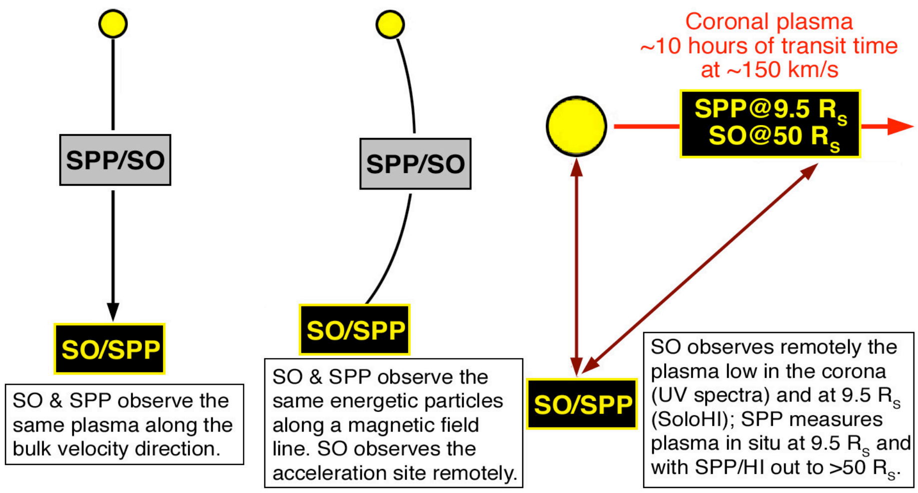

Figure 4.2 Solar Orbiter (SO) and Solar Probe Plus (SPP) will provide multiple opportunities for coordinated observations from complementary vantage points

When Solar Orbiter enters the high latitude phase of its mission, alignments with SPP will allow latitude gradient studies. Since both spacecraft's orbital motions are in the same direction, these alignment periods can range from a few days to over a month, depending on the radial distances at the time. Finally, there are many periods during which Solar Orbiter, Solar Probe Plus, and Earth lie within a 30° - 60° wedge, which is ideal for studies of larger structures such as high-speed streams, or large CME-driven interplanetary shocks.

Solar-C (status mid-2010). JAXA's Solar-C is a next-generation Japanese solar physics satellite that is presently under study. Following the great success of Hinode, an international Solar-C Working Group is, together with JAXA, developing the mission concept of Solar-C. Many different Solar-C mission concepts have been discussed, and there will certainly be synergies between Solar-C and Solar Orbiter that can be exploited once Solar-C becomes defined.

Other missions in the planning stage may contribute to heliophysical science and will be coordinated under the ILWS initiative.

4.4.2 Ground-Based Observations Supporting Solar Orbiter Science

Ground-based instruments in the visible and radio range will support Solar Orbiter observations. Spectro-polarimetric on-disk observations in the visible and infrared will provide the photospheric magnetic field vector from a different viewing angle (with the Advanced Technology Solar Telescope (ATST) and the European Solar Telescope (EST)). Coronagraphic observations of the density and the magnetic field vector in the corona (with the Coronal Solar Magnetism Observatory (COSMO)) will be most valuable, especially during perihelia in quadrature and give plasma properties in the coronal region observed by Solar Orbiter from straight above. Radio observations with the large arrays of LOFAR (Low Frequency Array) and ALMA (Atacama Large Millimeter Array) will allow high-resolution observations of the thermal and magnetic structure of the chromosphere and the corona. Availability of the Global Oscillation Network Group (GONG) or a similar successor will make it possible to carry out stereoscopic helioseismology for the first time, probing the deep interior of the Sun.

4.5 Theory, Modelling, and Scientific Closure

Underlying the science objectives of Solar Orbiter are some of the most important outstanding questions in solar and heliospheric physics, and more generally in plasma astrophysics, today. They are also some of the most challenging, namely the complex coupling of physical processes across multiple spatial and temporal scales. Microscopic physical processes lead to the formation of macroscopic solar wind streams; kinetic, small-scale processes combine with large-scale ones (e.g., to accelerate particles in shocks or compression regions); CME evolution is determined by its micro- and macroscopic interaction with the ambient corona and solar wind. The powerful high-resolution and high-cadence measurements during co-rotation will allow Solar Orbiter to discriminate between spatial and temporal variations and to correlate small-scale solar phenomena with larger ones both remotely and in-situ. Solar Orbiter's instrumentation and observational strategy are innovatively designed to tackle these problems, to understand the coupling from the global MHD scales of the Sun's corona to the local kinetic scales of wave and particle distributions in the heliosphere.

However, observations alone will not be sufficient. Theory and modelling will be key to provide the interpretive framework and also be required to elucidate the multi-scale connections among the coronal and heliospheric phenomena observed. Theory and modelling efforts are integral parts of the Solar Orbiter mission and each instrument team has equally talented scientists responsible for the theory and modelling aspects of their investigations.

Moreover, our understanding of both global and local processes has advanced considerably in recent years. Several large-scale programs are under way in Europe, the U.S., and worldwide to develop global MHD models that encompass the whole corona-heliosphere system. At the same time, there have been broad advances in theories for basic mechanisms such as particle acceleration and reconnection in collisionless plasmas. We expect that the theories and models will greatly increase in sophistication during the next five to ten years, and that Solar Orbiter will play a key role in testing and refining these powerful new models. For example, data-driven 3D MHD models of the initiation and development of solar wind streams and CMEs are now being developed and should be in a production state by the time Solar Orbiter delivers data. One of the crucial missing items for such models have been measurements of the photospheric field on the *entire* 4-π steradian surface of the Sun, not just the one half which happens to face the Earth at any given time. Thus Solar Orbiter will not only provide fundamentally new and important missing data, but also provide a powerful tool to verify model predictions and provide quantitative information about the state of the heliosphere in a wide range of latitudes and heliocentric distances.

Table 4.1 Required observations and instrumentation for Science Objective 1.

Objective 1: How and where does the solar wind plasma and magnetic field originate in the corona?
1.1 What are the source regions of the solar wind and heliospheric magnetic field?
• Composition of source regions (SPICE) and in-situ (SWA) • Determine magnetic connectivity (STIX, RPW, EPD, SWA) • Full disk photospheric magnetic fields (PHI) • In situ magnetic field (MAG) • Full Sun, high-resolution and spectral images of corona and chromosphere (EUI, SPICE, METIS) • Global maps of H and He flow velocities and He fractions (METIS, SoloHI)
1.2 What mechanisms heat and accelerate the solar wind?
• High-resolution images of the photospheric magnetic field (PHI) • High-resolution images of coronal loops, and evolving structures (EUI, SPICE) • Wave propagation and heating (SPICE) • H and He flow velocities (SPICE, METIS) • Velocities and mass density of evolving structures (SoloHI, METIS) • Composition and plasma properties of associated wind (SWA, MAG, RPW) • Distribution of smallest flares and solar particle events (STIX, EPD)
1.3 What are the sources of solar wind turbulence and how does it evolve?
• High-cadence measurements of the plasma micro state across a wide band of heliolatitudes for all relevant solar wind regimes and heliocentric distances (MAG, SWA, RPW) • Images of source regions in Doppler-broadened lines (SPICE) • Identify dropouts and measure scattering of SEPs by turbulence (EPD) • Time history of velocity and brightness of solar wind features and turbulence (METIS, SoloHI) • High-resolution, high-cadence maps of photospheric magnetic field (PHI)

Table 4.2 Required observations and instrumentation for Science Objective 2.

Objective 2: How do solar transients drive heliospheric variability?
2.1 How do CMEs evolve through the corona and inner heliosphere?
• High-resolution maps of photospheric magnetic field (PHI) • Map CME source location, expansion, rotation, and composition through corona (EUI, SPICE, STIX) • Link CME to in-situ properties (MAG, RPW, SWA, EPD) • Link evolution of CME properties in the corona to those measured in-situ (SoloHI, METIS) • Distribution of energy into heat, particle acceleration, and bulk kinetic energy (SWA, MAG, EPD)
2.2 How do CMEs contribute to solar magnetic flux and helicity balance?
• In-situ properties of ejecta (SWA, MAG, RPW) • Full-disk maps of photospheric magnetic field to determine source region helicity (PHI) • Map source regions to in-situ properties magnetic connectivity, polarity, and helicity (EUI, METIS,

SPICE, SoloHI, SWA, MAG, EPD)
2.3 How and where do shocks form in the corona?
• Global maps of electron density, H & He flow velocities (METIS) • Position and speed of shocks (SPICE, METIS, SoloHI, RPW EUI) • Full-sun and high-resolution coronal and chromospheric images (EUI, STIX, METIS, SPICE) • Location, intensity, thermal/non-thermal distribution of erupting regions (SoloHI, RPW, EPD) • Timing of eruptions and coronal manifestations (EUI, SoloHI, METIS, EPD) • Plasma, electric and magnetic fields in-situ (SWA, MAG, RPW, EPD)

Table 4.3 Required observations and instrumentation for Science Objective 3.

Objective 3: How do solar eruptions produce energetic particle radiation that fills the heliosphere?
3.1 How and where are energetic particles accelerated at the Sun?
• UV, white light and X-ray imaging of loops, flares, and CMEs (EUI, SPICE, STIX, METIS, SoloHI) • Global maps of electron densities, H, He flow velocities (METIS) • Image coronal suprathermal seed population (SPICE) • Location, timing, and motion of CMEs and shocks (EUI, SoloHI, METIS, EPD) • X-ray signatures of energetic particle interactions at loop footpoints, or on loops themselves (STIX) • Radio signatures of coronal shocks and escaping electrons (RPW) • Magnetic field, plasma wave and solar wind measurements to determine turbulence levels and identify shock passages (MAG, RPW, SWA) • Seed population specification from the heavy ion composition of solar wind and suprathermals in the inner heliosphere (SWA, EPD) • Velocity distributions, scattering characteristics, spectra and composition of energetic particles (EPD) • Timing and properties of small events (STIX, EPD, RPW, EUI) • Images of longitudinal extent of CMEs in visible, UV, and hard X-rays (SoloHI, METIS, EUI, SPICE, STIX)
3.2 How are energetic particles released from their sources and distributed in space and time?
• Timing, location, and intensity profiles of EUV, radio, and X-ray emissions in relation to energetic-particle intensities at a wide range of energies (EUI, SPICE, RPW, STIX, EPD) • X-ray spectral images of flaring regions (STIX) • High-resolution, high-cadence maps of photospheric magnetic field (PHI) • Turbulence properties throughout the inner heliosphere and corona (MAG, SWA, RPW, SPICE, EPD, METIS) • Magnetic connectivity (SWA, MAG, EPD)
3.3 What are the seed populations for energetic particles?
• Map coronal supra-thermal ion pool (SPICE) • Map inner-heliosphere supra-thermal ions (EPD, SWA) • Shock and turbulence parameters (MAG, SWA, RPW)

Table 4.4 Required observations and instrumentation for Science Objective 4.

Objective 4 How does the solar dynamo work and drive connections between the Sun and the heliosphere?
4.1 How is magnetic flux transported to and re-processed at high solar latitudes?
• Full-disk & high-resolution maps of the photospheric magnetic field and local and convective flows, maps of rotation, differential rotation, and meridional circulation, structure of subduction areas, properties of sub-surface convection cells (PHI) • High-resolution images of small-scale magnetic features at the poles (EUI, SPICE, PHI)
4.2 What are the properties of the magnetic field at high solar latitudes?
• Amount, distribution, and evolution of polar photospheric magnetic flux transversal magnetic field (PHI) • Magnetic fields, plasma flows, and temperatures of polar regions (PHI, EUI, SPICE, METIS) • Images of coronal and heliospheric structure in visible, UV and EUV (EUI, METIS, SoloHI) • Properties of bulk solar wind (SWA, MAG) • Magnetic connectivity (SWA, MAG, EPD, EUI)
4.3 Are there separate dynamo processes acting in the Sun?
• Latitudinal distribution of small-scale, emerging magnetic flux (PHI)

Table 4.5 Measurement and instrument requirements.

Required Observations (from Tables 4.1 – 4.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Global maps of H and He flow velocities and He abundance	METIS: coronal imaging in visible, H I and He II Ly-alpha lines, polarization brightness	<u>Polarized visible-light imaging:</u> Physical quantity: electron density FOV: annular between ~1.4 and 3.0 R_s. (at 0.28 AU) ; 4.3 - 11 R_s (at 0.8 AU) Spatial res:< 10^4 km at 0.28 AU Spectral coverage: 500-650 nm Cadence: 5 min. (CMEs obs.) <u>UV & EUV imaging:</u> Physical quantities: hydrogen and singly-ionized helium densities, and outflow velocities FOV: annular between ~1.4 and 3.0 R_s. (at 0.28 AU); extendable to 4.3 - 11 R_s (at 0.8 AU) Spatial resolution:< 10^4 km at 0.28 AU Spectral coverage: HI Ly-α, 121.6 nm; HeII Ly-α, 30.4 nm Spectral Resolution: $\Delta\lambda/\lambda \leq 10^{-1}$ Cadence: ~< 15 – 20 min. Substantial coverage of the Solar Probe Plus orbit	1.4 -3.0 R_s at 0.28 AU at 20" at 20s/20min/1hr cadence (vis/UV/EUV)
Mapping of coronal features to inner heliosphere, evolution of velocities and mass densities of coronal structures	SoloHI: White light, polarization brightness imaging	<u>Visible-light imaging:</u> Physical quantity: electron distribution FOV: 5.5° – 40.5° Spatial res: 2.7 arcmin Stray-light rejection: 10^{-14} B/B_s Cadence: 15-30 min.	FOV: 40°x40° at better than 1.9'/pixel

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 4.1 – 4.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Composition of coronal source region	SPICE: imaging EUV spectroscopy in two channels (plus one 2^{nd} order band) METIS (coronal imaging): visible, H I and He II Ly α lines, polarized brightness	**On disk:** SPICE: - Best spatial resolution 1" - Instantaneous FOV = 16 arcmin x 1 arcsec - Rastered FOV = 16 arcmin x 4 arcmin - Two lines per temperature decade - Exposure time 5 s - Spectral cadence of 20 min - Compositional signatures **Off disk:** SPICE: - Spatial resolution 1' - Stare (no raster) - Spectral cadence of 10 min - Radial coverage out to 2 R_s - Compositional signatures and outflow METIS: see above in table, He abundance	(1, 2, and 6)" x 17' slits 1"/pixel and 76mÅ/pixel Cadence: 16 min per raster 4" resolution rastered 5 min cadence 1.0 – 3.0 R_s METIS: (see above in table)
Composition of solar wind and compositional changes at solar wind boundaries	SWA: Mass, charge, energy of ions	Many heavy ion 1-D energy spectra (0.5 – 60 keV/q, 5% energy resolution); FOV = ±25°; cadence: up to 1 min at 0.3AU	SWA-HIS: 3-D VDFs, FOV=(-30°-+66°) x (-17°-+22.5°), 0.5 – 100 keV/e, 5.6% resolution, 5 min cadence, 30s burst mode (heavy ions) 3s (α particles) sensitivity ~$2 \cdot 10^{-5}$
Full-disk and high-resolution EUV images of chromosphere and corona	EUI: 174 and 304 A and HI Ly-alpha	**(a) FSI:** 2 passbands (cool/hot), 5.5° FOV, 7.2"/pixel, 1 min maximum cadence, SNR>10 in QS (dimmings) and off-limb (CME ejecta) **(b) HRI:** 2 passbands, 17 arcmin FOV, >1k format, 5 s cadence in burst mode, SNR>10 on AR loops (nanoflares)	FSI: 5.2° x 5.2° at 9" resolution, cool and hot passbands (He II 304Å) and Fe IX/X 174Å) HRI: 1000" at 1" resolution Ly-α (1216Å), Fe IX/X (174Å)
In-situ magnetic field properties	MAG: magnetic field vector	±1000 nT, 0.5nT absolute precision; 0-20 Hz	Ranges: from ±32 nT to ±2048 nT at ~ 4 pT resolution, up to 128 vectors/sec

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 4.1 – 4.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
High-cadence plasma properties	SWA: proton and electron E/q spectra MAG: magnetic field vectors	**Solar wind protons:** Detailed 3-dim velocity distribution functions at 10s time-resolution; FOV: ± 45° to Sun, ± 15° north/south, angular resolution of 2° **Solar wind electrons:** 3-D velocity distribution functions (about 5 -5000 eV, 10% energy resolution); 10s resolution MAG: already covered by previous requirements (see above in table) (MAG vectors will be used to derive reduced high-cadence VDFs by SWA)	SWA/PAS: up to 1/10s (in burst mode), FOV = (-24° - + 42°) x (± 22.5°), resolution < 2° SWA/EAS: FOV = (360° x (± 45°) on 2 orthogonal sensors for near 4π steradian total FOV, 1 eV – 5 kV, 10% resolution, 3s/10s cadence, 0.125 s in burst mode
Full-disk and high-resolution images of photospheric magnetic field	PHI: Stokes parameters of Fe I 617.3 nm line	**High-Res Mode:** Vector magnetic field with accuracy of 0.1 G (longitudinal), 20 G (transverse); 15'x15' FOV; resolution 1'' (0.5'' pixel size); Cadence: 1 min over selected periods of time; **Low-Res. (full disk) Mode:** Vector magnetic field with accuracy of 0.1 G (longitudinal), 20 G (transverse); Pixel size: ~5''; Cadence: 1 min. over selected periods of time FOV: >150' (full apparent Sun)	PHI/HRT: Accuracy: 0.1 G/14 G 16.8'x16.8' at 150 km (at 0.29 AU) 1.11 arcsec at 617.3 nm; 45-60 sec cadence PHI/FDT: accuracy same as for HRT Cadence: 45-60s FOV > 156'
High-resolution images of loops	EUI: high-resolution EUV images	EUI: already covered by previous requirements (see above in table)	See above in table EUI/HRI resolution
Wave propagation and heating	SPICE: Doppler broadening of lines; RPW: spectra and waveforms; METIS: coronal density fluctuations and Doppler broadening of H I and He II Ly α lines in a sector of the corona;	SPICE: already covered by previous requirements (see above in table), plus motions to ± 5km/s **Radio waves,** 3-axis electric and magnetic spectra and correlations; frequency range: 100 kHz to 20 MHz METIS (coronal imaging): see above in table + METIS (coronal spectroscopy): intensity, profile and Doppler shift of H I and He II Ly α lines at three radial positions (1.4°, 1.7°, 2.0°) from Sun center at equatorial latitudes around West limb (32° sector)	SPICE: see above in table; RPW: range from μV/m to V/m, down to near-DC METIS (coronal spectroscopy): Slit radial position: 1.4°, 1.7°, 2° Slit extension 0.8° Spatial res.: 34 " Spectral res: 0.054 nm (H I), 0.013 nm (He II) Cadence: 0.5 – 20 min

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 4.1 – 4.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Magnetic connectivity	MAG: local field direction SWA: halo/strahl electron pitch-angle distribution	MAG: already covered by previous requirements (see above in table) SWA: electrons FOV at least 2 π solid angle, ideally ± 180° to Sun, ± 45° north/south, angular resolution 10°, core-halo electron pitch-angle distributions with strahl population; While MAG provides B vector, strahl electrons and pitch-angle distributions give connectivity.	MAG: see above in table SWA/EAS: two orthogonal heads covering 2 π each, 32 azimuth bins by (16-32) elevation bins
X-ray imaging of loops, flares	STIX: high-resolution energy-resolved X-ray images of loops and footpoints	Energy range: 4 to 150 keV; Energy resolution: ΔE/E ~0.2 FWHM; Angular Resolution: <~7 arcsec; FOV for imaging: >~20 arcmin; FOV for source centroid location: Full Sun at 0.29 AU, i.e. ~150 arcmin; Effective area ~ 5 cm^2; time resolution (for flares) <~5 s	STIX: range: 4 – 150 keV, Resolution: 1 keV@ 6 keV, 15 keV @ 150 keV;imaging at scales from 7" to 8.8', field-of-view for imaging of 1.5 degree, source centroid location over full Sun at all radial distances,, effective area 6.4 cm^2,<0.1s time resolution
Timing of radio emissions	RPW: magnetic/electric fields	3-axis electric and magnetic spectra and correlations; frequency range: 100 kHz to 20 MHz	From DC to 20 MHz/500 kHz (electric/magnetic) at up to 500kS/s
Timing of EUV emission	EUI: high-cadence imaging	10s or better cadence	EUI: up to 2s typical for EUV, sub-second in high-cadence mode for Ly α
Timing of energetic particles	EPD: proton/e^- measurements: particle intensities in various energy ranges, velocity dispersion, different species	**Electrons:** Energy range: ~2 keV to ~1 MeV, energy resolution: ΔE/E ~0.2, geometry factor > ~0.1-1 cm^2sr; time resolution 10 s at < 0.5 AU, 1 min >0.5 AU **Protons:** Energy range: 0.005 to >100 MeV; energy resolution: ΔE/E ~0.2; geometry factor >~0.1-1 cm^2sr; time resolution 20 s below 10 MeV at <0.5 AU, 1 min > 0.5 AU	EPD/EPT: up to 1s in burst mode, electrons 2 keV-30 MeV; protons: 2 keV - 7 MeV

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 4.1 – 4.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Turbulence levels	MAG: high-cadence magnetic field RPW: high-cadence electric and magnetic field, power spectral densities SWA: high-cadence bulk ion and electron properties, EPD: electron and proton anisotropies	MAG: already covered by previous requirements (see above in table) Plasma wave electric spectra for thermal-noise spectroscopy; sensitivity: 3 nV/Hz$^{1/2}$; frequency range: 10-800 kHz. Electric and magnetic spectra and waveforms in an internal burst mode (triggered internally or on input), frequency range: near DC to 1 MHz; AC Magnetic Fields: 10Hz – 10kHz; waveform capture already covered by previous requirement (see above in table) **electrons:** angular resolution 30° over 60° FOV as close to Sun as possible; **protons:** two angular sectors from 0-90° as close to the Sun as possible up to 10 MeV	MAG: see above in table RPW: see above in table, up to 500 kS/s SWA: see above in table EPD: up to 1s (burst mode), EPT/HET: 4 FOVs, LET 6 FOVs
Supra-thermal seed population	EPD: suprathermal particle composition	**Heavy Ions:** He – Fe, energy range: 0.02 – 100 MeV/nucleon (species dependent) Composition: separate ^{3}He, ^{4}He, C, N, O and Fe as a minimum; energy resolution: $\Delta E/E$ ~0.2; geometry factor >~0.1-1 cm^{2}sr; time resolution 30 s <0.5 AU, 1min >0.5AU	EPD/SIS: 0.21 cm^2 sr geom. fact; ^{3}He, major species He-Fe, delta E/E <0.1; range 0.008 – 10 MeV/nuc
Solar wind bulk properties	SWA: electron, proton, alpha-particle velocities, temperatures, densities	SWA: already covered by previous requirements (see above in table)	SWA: ~3s cadence
Distribution of smallest flares and solar particle events	EPD: small flux events STIX: high X-ray intensity	EPD: already covered by previous requirement (see above in table) STIX: already covered by previous requirements (see above in table) While STIX will observe bremsstrahlung emission in the X-ray range from energetic electrons at the Sun, EPD will measure the properties of the escaping particles to determine to determine the energy content in energetic particles.	EPD: Low noise detectors & FEE, large geometric factor (>0.1 cm^{2}sr), LET up to 1.7 cm^{2}sr in single-detector mode STIX: 6.4 cm^2 effective area

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
High-cadence measurements of the plasma micro state across a wide band of helio-latitudes for all relevant solar wind regimes and heliocentric distances	MAG: high-cadence magnetic field SWA: high-cadence 2-D electron/proton VDFs, composition RPW: high-cadence electric and magnetic field spectra, wave forms	MAG, SWA, RPW: already covered by previous requirements (see above in table) Accurate timing between the three instruments is ensured by SpaceWire time signal to in-situ payload. Occasional burst modes chosen such as to cover all solar wind regimes at all distances and latitudes. Burst mode coordinated between in situ instruments. Composition will be used to determine coronal origin of solar wind.	MAG: see above in table SWA: 0.125s e-, 0.1s protons, 3s alpha articles, 30s heavy ions RPW: low frequency (near DC up to local plasma frequency) and time-domain sampling, at up to 500 kS/s
Images of source regions in Doppler-broadened lines	SPICE: on-disk and limb imaging spectroscopy in UV METIS: off-limb imaging-spectroscopy in H I and He II Ly α lines	SPICE: already covered by previous requirements (see above in table) METIS: already covered by previous requirements (see above in table)	SPICE: see above in table METIS: see above in table
Identify dropouts and measure scattering of SEPs by turbulence	EPD: intensities and anisotropies of low-energy ions, protons and electrons MAG: B-vectors SWA: bulk solar wind	EPD: already covered by previous requirements (see above in table) At least 1st-order anisotropies (forward-backward) Use velocity dispersion plots in conjunction with pitch-angle distributions and correlate with solar wind turbulence levels and variations at the coronal source.	EPD:/STEIN: few keV – 100 keV e/p, 1storder anisotropy EPD/EPT: 20 – 400 keV electrons, 20 – 7 MeV protons, 4 FOVs EPD/LET: low-energy protons in 6 FOVs EPD/SIS: 0.01-10 MeV/nuc heavy ions

Time history of velocity and brightness of solar wind features and turbulence	METIS: high-cadence visible, H I and He II Ly-alpha lines; SoloHI: white-light and pB	METIS: already covered by previous requirements (see above in table) Derive acceleration and heating properties from time-height and time-brightness plots. SoloHI: Provide density power spectra in selected regions along the ecliptic path of the s/c and compare with SWA measurements.	METIS: see above in table at 20 min cadence; SoloHI: 2° x 5° FOV centered at 7, 15, 20 Rsun at 0.28 AU, 10 sec – 2 min cadence with SNR > 16
High-resolution, high-cadence maps of photospheric magnetic field	PHI: Stokes parameters	PHI: already covered by previous requirements (see above in table)	PHI: see above in table

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Map CME source location, expansion, rotation, and composition through corona	STIX: X-ray source location of associated flare EUI: high-resolution images of source region SPICE: on-disk and limb imaging spectroscopy METIS: H and He flow velocities, electron densities SoloHI: track to inner heliosphere RPW: radio emission	STIX, EUI, SPICE, METIS, SoloHI, RPW: already covered by previous requirements (see above in table) Coordinated observations focusing on promising active region. STIX/EUI measure associated flare, SPICE/METIS flow velocities, expansion of different ions, SoloHI tracks to interplanetary space, while RPW measures radio emission from accelerated electrons at local plasma frequency (compare with METIS e^- density)	STIX, EUI, SPICE, METIS, SoloHI: see above in table RPW: up to 20 MHz
Map CMEs to in-situ properties	PHI: high-resolution photospheric magnetic field EUI: high-resolution images of source region SPICE: composition of source region	PHI, EUI, SPICE, METIS, SWA, RPW, MAG: already covered by previous requirements (see above in table) While EUI and STIX provide context and timing, SPICE gives composition, for comparison with SWA composition. Compare PHI and MAG field data, track evolution with	PHI, EUI, SPICE, METIS: see above in table SWA: elemental and charge-state composition

	SWA: composition of in-situ CME RPW: time history of (type II) radio emission MAG: in-situ magnetic field rotation METIS: track CMEs in inner corona (coronal images in visible, H I and He II Ly α lines) SoloHI: image large-scale heliospheric structures , track CMEs to inner heliosphere	RPW, METIS, SoloHI SoloHI: Use statistical properties of CMEs to link them to in-situ properties. When Solar Probe Plus is appropriately located, compare with in-situ data.	RPW: up to 20 MHz MAG: see above in table

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Distribution of energy into heat, particle acceleration, and bulk kinetic energy	SWA: 3-D velocity distribution functions, bulk speed MAG: magnetic pressure EPD: particle spectra	SWA, MAG, EPD: already covered by previous requirements (see above in table) Measure directly, in-situ, the energy content in the various forms and acquire distribution as statistics build up.	SWA, MAG, EPD: normal operation mode
Energetic particle timing	EPD: particle intensities in different energy ranges and for different species	EPD: already covered by previous requirements (see above in table)	EPD: burst mode intervals
Image coronal suprathermal population	SPICE: imaging UV spectroscopy	SPICE: already covered by previous requirements (see above in table) Excellent signal to noise ratio, low background Use intensity differences in highly Doppler-broadened lines	SPICE: see above in table
X-ray signatures of energetic particle interactions at loop footpoints or on loops themselves	STIX: high-cadence, energy resolved imaging	STIX: already covered by previous requirements (see above in table)	STIX: see above in table
Radio signatures of coronal shocks and escaping electrons	RPW: Type II and III radio	RPW: already covered by previous requirements (see above in table)	RPW: see above in table

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Magnetic field, plasma wave, and solar wind measurements to determine turbulence levels and shock passage	MAG: high-cadence magnetic field RPW: high-cadence electric/magnetic field SWA: high-cadence bulk plasma properties, 2-D VDFs,	MAG, RPW, SWA: already covered by previous requirements (see above in table) Use RPW of MAG to trigger in-situ suite. MAG and SWA data provide Alfvén velocity and turbulence parameters such as Elsässer variables; RPW measures electric field properties which influence solar wind electron and proton VDFs.	MAG: burst mode (128 vectors/s) RPW, SWA: burst mode
Seed population specification from the heavy ion composition of solar wind and suprathermals in the heliosphere	SWA: heavy ion composition and long-term velocity distribution functions EPD: suprathermal particle population	SWA: already covered by previous requirements (see above in table) This drives upper range of HIS energy band (100 keV/e) EPD: already covered by previous requirements (see above in table) Cross calibrated SWA and EPD/SIS fluences over a wide range in latitudes and distance	SWA: normal operation mode EPD/SIS: normal operation mode high latitudes and full radial coverage
Timing, velocity distributions, scattering characteristics, spectra and composition of energetic particles, continuous spectra of multiple heavy ion species in energy range 0.1–100 MeV/n	EPD: full composition, anisotropies, energy coverage, occasional high-cadence studies; Resolution of 3He and multiple heavy ion species	EPD: already covered by previous requirements (see above in table)	EPD: 2keV-20 MeV e-, 3keV – 100 MeV p, 8keV/n – 200 MeV/n ions continuous coverage with geometric factors > 0.1 cm^2sr 4 – 20 keV neutrals, normal operation, occasional burst mode

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected payload capability**
Timing of EUV, radio, and X-ray emissions in relation to energetic particle intensities at a wide range of energies	EUI, STIX: high-cadence imaging of active region, trigger to EPD RPW: type II and type III radio emission EPD: staggered high-cadence measurements of particle intensities	EUI, STIX, RPW, EPD: already covered by previous requirements (see above in table) EUI/STIX provide trigger to EPD. RPW gives shock location (if present) from radio emission, and EPD determines particle properties. HET and EPT (for electrons) are triggered first, lower energy LET later (velocity dispersion)	EUI, STIX, RPW, EPD: see above in table
Full-disk & high-resolution maps of the photospheric magnetic field and local and convective flows, maps of rotation, differential rotation, and meridional circulation, structure of subduction areas, properties of sub-surface convection cells;	PHI: full-disk and high-resolution Stokes parameters, Doppler shifts, intensity variations	**High-Res Mode:** Vector magnetic field with accuracy of 0.1 G (longitudinal), 20 G (transverse); Doppler velocity with accuracy of 15 m/s; Continuum images with accuracy of 0.5% (flat field uniformity) 15'x15' FOV; resolution 1'' (0.5'' pixel size); Cadence: 1 min over selected periods of time; **Low-Res. (full disk) Mode:** Vector magnetic field with accuracy of 0.1 G (longitudinal), 20 G (transverse); Doppler velocity with accuracy of 15 m/s; Continuum images with accuracy of 0.5% (flat field uniformity) Pixel size: ~5''; Cadence: 1 min. over selected periods of time FOV: >150' (full apparent Sun)	PHI/HRT: Accuracy: 0.1 G/14 G; 7 m/s; 0.5% 16.8'x16.8' FOV, 1.11" resolution at 617.3 nm; 45-60 sec cadence PHI/FDT: accuracy same as for HRT Cadence: 45-60s FOV > 156'
High-resolution images of small-scale magnetic features at the poles	EUI: high-resolution EUV images SPICE: high-resolution spectroscopy PHI: high-resolution Stokes parameters	EUI, SPICE, PHI: already covered by previous requirements (see above in table) Coordinated high-resolution FOVs	EUI, SPICE, PHI: normal operation mode

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Amount, distribution, and evolution of polar photospheric magnetic flux	PHI: full-disk and high-resolution Stokes parameters	PHI: already covered by previous requirements (see above in table)	PHI: normal operation mode
Transversal magnetic field in the photosphere	PHI: high-resolution Stokes parameters other remote-sensing observations (e.g. SDO/HMI)	PHI: already covered by previous requirements (see above in table)	PHI: normal operation
Latitudinal distribution of small-scale, emerging magnetic flux in the photosphere	PHI: high-resolution Stokes parameters	PHI: already covered by previous requirements (see above in table)	PHI: normal operation mode large latitude coverage
Position and speed of shocks;	METIS: flow velocities, electron densities SoloHI: white-light coronagraphy SPICE: temperatures from Doppler-broadened lines RPW: radio emissions	METIS, SoloHI, SPICE, RPW: already covered by previous requirements (see above in table) Use METIS electro-density maps to pinpoint radio emission and compare with RPW type-II radio bursts. Compare speeds of features in METIS/SPICE with derived velocities, use temperatures and magnetic field extrapolations to determine magnetosonic speed and compare with shock speed. Follow shocks in SoloHI images and extract speed and density profile	METIS, SPICE, RPW: see above in table SoloHI: FOV 5.5°-45.5, cadence 6-15 min
High-cadence microphysics of plasma	SWA: burst mode 2-d velocity distribution functions MAG, EPD: burst mode RPW: burst mode trigger to in-situ	SWA, MAG, EPD, RPW: already covered by previous requirements (see above in table)	SWA, MAG, EPD, RPW: see above in table

Table 4.5 Measurement and instrument requirements (cont'd).

Required Observations (from Tables 3.1 – 3.4)	**Instrument: Measurement**	**Measurement Requirements and Coordinated Observation Plans**	**Selected Payload Capability**
Timing and properties of small events	STIX: high-cadence, high-resolution EUI: high-cadence, high-resolution images EPD: energy spectra of electrons and protons RPW: high-cadence	STIX, EUI, EPD: already covered by previous requirements (see above in table) RPW: already covered by previous requirements (see above in table), low background, low noise	STIX, EUI, EPD, RPW: see above in table
Images of longitudinal extent of CMEs in visible and UV	METIS: flow velocities SoloHI: white light EUI: UV images	METIS, SoloHI, EUI: already covered by previous requirements (see above in table)	High latitudes
Magnetic fields, plasma flows, and temperatures of polar regions	PHI: high-resolution photospheric magnetic field EUI: high-resolution EUV images SPICE: high-resolution images, Doppler-broadened lines METIS: H I and He II flow velocities	PHI, EUI, SPICE, METIS: already covered by previous requirements (see above in table)	PHI, EUI, SPICE, METIS: see above in table
Images of coronal and heliospheric structure in visible and EUV;	METIS: electron density, H, He flows SoloHI: white-light images of corona EUI: coronal images	METIS, SoloHI, EUI: already covered by previous requirements (see above in table)	METIS, SoloHI, EUI: see above in table
Images of evolution of coronal hole boundaries	EUI: full-disk images in EUV METIS: images of coronal holes boundaries in the inner corona SoloHI: images of coronal hole boundaries in the inner heliosphere	EUI, METIS, SoloHI: already covered by previous requirements (see above in table) Make available as data product for comparison with in-situ data and observations from near-Earth assets.	EUI, METIS, SoloHI: see above in table

Table 4.6 Overview of the selected Solar Orbiter payload.

Investigation	PI	Countries	Measurement	Technique
Solar Wind Analyzer (SWA)	C. Owen, MSSL, UK	UK, I, F, JP, D, CH, USA	Solar wind ion and electron bulk properties, ion composition (1eV- 5 keV electrons; 0.2 - 100 keV/q ions)	Multiple sensors (electrons, proton/alpha, heavy ions); electrostatic deflection, time-of-flight measurement, solid state detectors
Energetic Particle Detector (EPD)	J. Rodríguez-Pacheco, Univ. of Alcala, E	E, D, FI, GR, CH, F, SK, USA	Composition, timing, and distribution functions of suprathermal and energetic particles (8 keV/n – 200 MeV/n ions; 20-700 keV electrons)	Multiple solid-state dE/dx vs E detector telescopes, time-of-flight measurement
Magnetometer (MAG)	T. Horbury, ICSTM, London, UK	UK, A, I, H, D, F, E, DK, USA	DC vector magnetic fields (0 – 64 Hz)	Dual fluxgate sensors
Radio & Plasma Waves (RPW)	M.Maksimovic, Obs. de Meudon, Paris, F	F, SE, CZ, NO, UK, A, D, GR, AU, I, H, FI, RU, USA	AC electric and magnetic fields (~DC – 20 MHz)	Electric antennas, Search Coil Magnetometer; Low-frequency and Thermal Noise/High-frequency receivers, Time-domain sampling
Polarimetric and Helioseismic Imager (PHI)	S. Solanki, MPS, Lindau, D	D, E, F, SE, NO, CH, AU, USA	Vector magnetic field and line-of-sight velocity in the photosphere	High-res. telescope: off-axis Ritchey-Chrétien, full-disk telescope: refractor, Fabry-Perot filtergraph
EUV Imager (EUI)	P. Rochus, CSL, Liege, B	B, UK, F, D, USA	Full-disk EUV and high-resolution EUV and Lyman-α imaging of the solar atmosphere	Full-Sun Imager: dual-band EUV off-axis Herschelian, 2 High-res. Imagers: single-band EUV and Ly α off-axis Ritchey-Chrétien
Spectral Imaging of the Coronal Environment (SPICE)	D. Hassler, SwRI, Boulder, USA	USA, UK, D, F, N	EUV spectroscopy of the solar disk and corona	Off-axis paraboloid telescope, TVLS grating spectrograph
X-ray Spectrometer Telescope (STIX)	A. Benz, ETH Zürich, CH	CH, PL, D, CZ, IRE, A, UK, F, USA	Solar thermal and non-thermal X-ray emission (4 – 150 keV)	Fourier transform imaging, CZT detectors
Coronagraph (METIS/COR)	E. Antonucci, INAF-OATo, Torino, I	I, D, CZ, F, GR, USA	Visible, UV and EUV imaging of the solar corona; UV/EUV spectroscopy of a coronal sector	Externally-occulted coronagraph
Heliospheric Imager (SolOHI)	R. Howard, NRL, Washington DC,USA	USA	White-light imaging of the extended corona; High cadence imaging of subregion	Wide-angle lens with linear occulter

APPENDIX A ACRONYMS

AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control Subsystem
APE	Absolute Pointing Error
APM	Antenna Pointing Mechanism
APS	Active Pixel Sensor
ASR	Assessment Study Report
AU	Astronomical Unit
CDPU	Common Data Processing Unit
CIR	Corotating Interaction Region
CME	Coronal Mass Ejection
CPS	Chemical Propulsion System
CVP	Checkout and Verification Phase
CZT	Cadmium-Zinc-Telluride
DC	Direct Current
DPU	Data Processing Unit
DPU	Digital Processing Unit
DSM	Deep Space Manoeuvres
DSN	Deep Space Network
EAS	Electron Analyzer System
EELV	Evolved Expendable Launch Vehicle
EPD	Energetic Particle Detector
EPS	Electrical Power Subsystem
EPT	Electron Proton Telescope
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
ESTRACK	ESA Tracking Station Network
EUI	Extreme Ultraviolet Imager
FDT	Full Disk Telescope
FEE	Front-end Electronics
FG	Filtergraph
FIP	First Ionization Potential
FOSO	Focused Opportunity for Solar Orbiter
FOV	Field of View
FSI	Full Sun Imager
GAM	Gravity Assist Manoeuvre
GI	Guest Investigator
HCS	Heliospheric Current Sheet
HELEX	Heliophysical Explorers
HET	High Energy Telescope

HIS	Heavy Ion Sensor
HMF	Heliospheric Magnetic Field
HRI	High Resolution Imager
HRT	High Resolution Telescope
HTHGA	High Temperature High Gain Antenna
IAPS	Intensified Active Pixel Sensor
ICU	Instrument Controller Unit
IDS	Interdisciplinary Scientist
IMF	Interplanetary Magnetic Field
IMU	Inertial Measurement Unit
JSTDT	Joint Science and Technology Definition Team
kS/s	Kilosamples per second
KSC	Kennedy Space Center
LCVR	Liquid Crystal Variable Retarders
LEOP	Launch and Early Orbit Phase
LET	Low Energy Telescope
LFR	Low Frequency Receiver
LGA	Low Gain Antenna
LOS	Line of Sight
LVPS	Low Voltage Power Supply
LWS	Living with a Star
MAG	Magnetometer
MEB	Main Electronics Box
METIS/COR	Multi Element Telescope for Imaging and Spectroscopy
MGA	Medium Gain Antenna
MLI	Multi-Layer Insulation
MOC	Mission Operations Centre
NASA	National Aeronautics and Space Administration
OBC	On-Board Computer
OBDH	On-Board Data Handling
OSR	Optical Solar Reflector
PAS	Proton Alpha Sensor
pB	Polarized Brightness
PCDU	Power Conditioning and Distribution Unit
PCU	Power Converter Unit
PHI	Polarimetric and Helioseismic Imager
PMP	Polarization Modulation Package
PRC	Payload Review Committee
RFDU/WUI	Radio-Frequency Distribution Unit / Wave Guide Interface
RIU	Remote Interface Unit
RPE	Relative Pointing Error
RPW	Radio Plasma Wave
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SAA	Solar Aspect Angle
SADE	Solar Array Drive Electronics
SADM	Solar Array Driving Mechanism
SCE	SoloHI Control Electronics
SCM	Search Coil Magnetometer

SEP	Solar Energetic Particle
SIM	SoloHI Instrument Module
SIS	Suprathermal Ion Spectrograph
SMEX	Small Explorer
SMP	Science Management Plan
SOAD	Science Operations Assumptions Document
SOC	Science Operations Centre
SOHO	Solar and Heliopsheric Observatory
SoloHI	Solar Orbiter Heliospheric Imager
SPC	Science Programme Committee
SPICE	Spectral Imaging of the Coronal Environment
SPP	Solar Probe Plus
SSMM	Solid State Mass Memory
STEIN	Suprathermal Electrons Ions and Neutrals
STEREO	Solar Terrestrial Relations Observatory
STIX	Spectrometer/Telescope for Imaging X-rays
SWA	Solar Wind Analyzer
SWT	Science Working Team
TCS	Thermal Control Subsystem
TDS	Time Domain Sampler
TNR-HFR	Thermal Noise and High Frequency Receiver
TOF	Time of Flight
TRACE	Transition Region and Coronal Explorer
TVLS	Toroidal Variable Line Space
UV	Ultraviolet