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DOCUMENT

Solar Orbiter
Science Operations Concept Document

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1 INTRODUCTION

1.1 Purpose and Scope

This document provides the definition of a mission specific Science Ground Segment (SGS) concept on operations and data analysis which fulfils the requirements in the Science Implementation Requirements Document (SIRD) [AD.01] and which considers the mission characteristics and concept drivers and constraints originating from external sources to the Science Operations Centre (SOC) such as the Mission Operations Centre (MOC), the Instrument Teams and lessons learned from other missions. This concept is the foundation of definition work of SOC systems and the detailed definition of operational activities and procedures at the SOC, but the analysis of the performance requirements is not specifically addressed and will be considered in the early development phase.

This document does not cover the final details of the science operations data tasks and does not describe the development of the SOC systems.

1.2 Applicable Documents

[AD.01] Solar Orbiter Science Implementation Requirements Document (SIRD).
[AD.02] Solar Orbiter Science Management Plan (SMP).

1.3 Reference Documents

[RD.01] Solar Orbiter Science Requirements Document.
[RD.02] Consolidated Report on Mission Analysis (CReMA).
[RD.03] Solar Orbiter Mission Operations Concept Document.
[RD.04] Solar Orbiter Definition Study Report (Red Book).
[RD.05] Solar Orbiter Engineering Guidelines for External Users

1.4 Abbreviations and Acronyms

AD	Applicable Document
AIV	Assembly, Integration, and Verification
CaC	Cost at Completion
CP	Cruise Phase
DM	Development Manager
EID-A	Experiment Interface Document, Part A
EID-B	Experiment Interface Document, Part B
EMP	Extended Mission Phase
EPD	Energetic Particle Detector

ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
ETB	Engineering Test Bench
EUI	Extreme UV Imager
FCP	Flight Control Procedure
FD	Flight Dynamics team at ESOC
FECS	Flight Event and Communication Skeleton
GAM	Gravity Assist Manoeuvre
HTHGA	High Temperatur High Gain Antenna
IIC	Inter-Instrument Communication (the entire onboard process of which Service-20 TCs are a part).
IOCR	In-Orbit Commissioning Review
IOR	Instrument Operational Request
IS	In-situ Instruments
LEOP	Launch and Early Orbit Phase
MAG	Magnetometer
METIS	Multi-Element Telescope for Imaging and Spectroscopy
MGS	Mission Ground Segment
MIRD	Mission Implementation Requirements Document
NECP	Near Earth Commissioning Phase
NMP	Nominal Mission Phase
OGS	Operational Ground Segment
OIRD	Operations Interface Requirements Document
OM	Operations Manager
OPS-PS	Operations Department Solar Orbiter
PHI	Polarimetric and Helioseismic Imager
PI	Principal Investigator
PM	Project Manager
PMP	Post Mission Phase
PS	Project Scientist
POR	Payload Operational Request (requests from SOC->MOC, mostly comprising checked/processed IORs)
PSF	Planning Skeleton File (in Solar Orbit context this is equivalent to the E-FECS)
PTR	Pointing Timeline Request
RD	Reference Document
RPW	Radio and Plasma Wave Instrument
RS	Remote Sensing Instruments
RSW	Remote Science Windows
SADM	Solar Array Drive Mechanism
SAT	Science Archive Team
SGS	Science Ground Segment
SIP	Science Implementation Plan
SIRD	Science Implementation Requirements Document
SMP	Science Management Plan
SO	Solar Orbiter

SOC	Science Operations Centre
SoloHI	Solar Orbiter Heliospheric Imager
SOMA	Solar Orbiter Mission Archive (the “operations” partition of the Science Archive)
SOOP	Solar Orbiter Observing Plan
SPICE	Spectral Imaging of the Coronal Environment
SPMP	Software Project Management Plan
SRE-PS	Solar Orbiter Project Team
SRE-SM	Science Missions Division of SRE
SRE	Science and Robotic Exploration Directorate
SRD	System Requirements Document
SSMM	Solid State Mass Memory
STIX	Spectrometer Telescope for Imaging X-rays
SVIP	SGS Verifying, Validation & Integration Plan
S/W	Software
SWA	Solar Wind Analyser
TBC	To Be Confirmed
TBD	To Be Determined
TBW	To Be Written
WRT	With Respect To

1.5 Document Outline

Chapter 1 describes the structure, purpose and scope of the document.
Chapter 2 gives an overview of the mission and the Science Operations Centre.
Chapter 3 analyses requirements and constraints, and identifies the drivers of the science operations concept.
Chapter 4 describes the concept in terms of process, activities, inputs, outputs and responsibilities.

2 OVERVIEW

2.1 Mission Description

Solar Orbiter's mission is to address the central question of heliophysics: *How does the Sun create and control the heliosphere?* 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.

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

- How and where do the solar wind plasma and magnetic field originate in the corona?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

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.

The near-Sun phase of the mission will enable the spacecraft to approach the Sun as close as 0.28 AU during part of its orbit. The angular speed of a spacecraft at this distance approaches the rotation rate of the Sun, so that the remote sensing instruments will be able to track a given point on the Sun surface for many days.

During the out of ecliptic phase of the mission, the spacecraft will reach higher solar latitudes (up to 34° close to the end of the mission), making possible detailed studies of the Sun's polar caps thanks to the remote sensing instruments.

The Solar Orbiter Science Requirements Document [RD.01], provides a more detailed discussion of the top scientific goals of the Solar Orbiter mission.

The Solar Orbiter spacecraft is a 3-axis stabilized platform that is Sun-pointed during all mission phases after LEOP with a heat shield that provides the platform and sensitive equipment with protection from the extremely high levels of solar flux. The heat shield also contains cut-outs with feed-throughs (and doors), which provide the remote-sensing instruments with their required field of view to the Sun. The spacecraft structure includes internal shear panels providing mounting locations for the remote-sensing instruments and bus units. One remote-sensing instrument (SOLO-HI) is mounted externally, and views part of the corona around the side of the heat-shield rather than through a feed-through. The in-situ payload units are mounted externally in various locations on the spacecraft: two sensors of SWA are exposed to direct sun through cut-outs in the corners of the heat-shield; MAG, SWA-EAS and the search-coil of RPW are mounted on a deployable boom lying within the umbra of the spacecraft body; three RPW antennas deploy radially, orthogonal to the sun-direction (and are therefore sun-illuminated), remaining IS units are located on the –Y or +Y panels. Solar arrays provide the capability to produce the required power throughout the mission over the wide range of Sun distances experienced, using rotation about their longitudinal axis to control the Solar Aspect Angle (SAA) in order to manage the array temperature throughout the mission and in particular during close approach to the Sun.

The launcher interface ring is located on the opposite face of the structure to the heat shield, such that the heat shield is uppermost when the S/C is mated to the launch vehicle. No main engine is included as the overall delta V requirements of the mission are comparatively modest. Rear-panel thrusters are complemented by additional thrusters on side panels in order to provide the capability to perform delta V manoeuvres whilst maintaining a Sun-pointing attitude when close to the Sun, a critical capability for Solar Orbiter.

An articulated High Temperature High Gain Antenna (HTHGA) provides nominal communication with the ground station, and a Medium Gain Antenna (MGA) and Low Gain antennas (LGA) are included for use as backup and during the LEOP.

The Solar Orbiter payload consists of 10 instruments with more than 30 detectors. Of these 10 instruments, 4 are designed for in-situ (IS) measurements and 6 for remote sensing (RS). Please refer to the SIRD [AD.01] for details about the Payload and the Principal Investigators.

Whilst the mission shares many features with typical interplanetary missions operated by ESA there are also some clear differences

- No planetary orbit. Therefore (outside of GAMs) no short-term orbital geometry changes, no planetary occultation of communications, no albedo, no eclipses, no rapidly changing attitude constraints, no significant drift in mission planning timings between LTP, MTP, STP.
- Dynamic target body (the Sun). Changing surface features that are not plannable in advance. Many instruments having burst-modes or other autonomous responses to events.
- Pericentre still very far from central body. Off-pointing limited to 1 deg from nadir. Platform operations comparatively unaffected by science off-pointings. Off-pointing slew durations comparatively short.
- Encounter type mission. Limited number of close approaches to the sun, meaning that a substantial part of the operations and science are compressed into a few

narrow windows. Limited opportunities to repeat observations that fail. This aspect is different wrt the both the solar and planetary missions that Solar Orbiter's SGS heritage is derived from.
- Emphasis on parallel observing/operations and the science that results from the combination of all instruments. This leads to complex observing goals that can't be expressed on a per-instrument basis.

2.2 Ground Segment

The Ground Segment for Solar Orbiter in the operational configuration consists of the following elements:

- The Operational Ground Segment (OGS) which includes the Mission Operations Centre (MOC) located at ESOC and the Ground Stations and Communication Network (ESTRACK).

- The Science Ground Segment (SGS) which includes the Science Operations Centre (SOC) located at ESAC and the PI facilities used to operate their respective instruments and perform data processing.

The OGS is responsible for all mission operations planning, execution, monitoring and control activities. The responsibilities of the SGS are described in the following section.

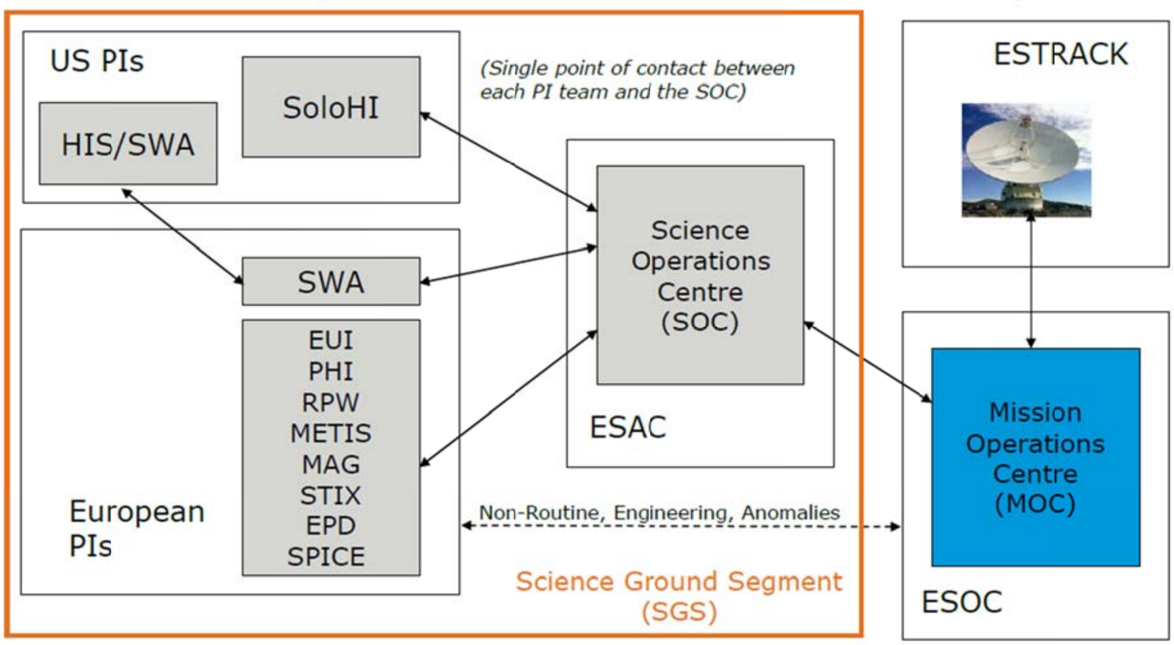

Figure 1: A Schematic drawing of the main components of the SGS and OGS.

2.3 Science Ground Segment

The Science Ground Segment is composed by the Science Operations Centre (SOC), located in the European Space Astronomy Centre (ESAC) near Madrid, Spain, and the infrastructure that the Instrument Teams use both to manage their respective instruments and to process and analyse their instrument telemetry in order to generate science data products usable for research by the scientific community.

The SOC is responsible for payload science operations preparatory activities and the coordination of the science operations plans of the Instrument Teams to generate a conflict free science operational timeline. This timeline will be prepared from inputs provided by the Instrument Teams and by the MOC. All nominal instrument planning and commanding activities after payload commissioning will take place through the SOC.

The Instrument Teams are expected to coordinate their observing plans, at their highest level, at the Science Working Team, chaired by the Project Scientist, and refine it further at the Science Operations Working Group. They are, then, expected to submit their Instrument Operations Requests to the SOC, along with any requests for special operations. The SOC will carry out a preliminary analysis of these observing plans to assess if they are feasible within overall mission constraints and provide feedback to the SWT and SOWG.

Once the observing plans are consolidated, the Instrument Teams define a more detailed science operations plan at the level of individual observations. The SOC will interface with the MOC to assess the feasibility of the requests based on available resource predictions by the SOC and spacecraft operational constraints from the MOC to verify whether the requested observations can be carried out. It is expected that the SOC, in the process of arriving to a conflict free schedule of science operations, will have access to a copy of the database of mission rules and constraints maintained by the MOC in order to avoid unnecessary iterations.

The planning of science operations, both at SOC and at the Instrument Teams, will be supported by a specially designed data set, the ‘low latency’ data, which will be downlinked in the very next ground station pass regardless of orbital geometry[1]. The uses of the low latency data are:

- Provide planning context information to the SOC and the Instrument Teams, in particular to determine spacecraft pointing.
- Assessment of instrument health and performance by the Instrument Teams.

[1] Excluding conjunctions and subsequent “catch up” periods.

- Support the decision process by the Instrument Teams of what telemetry to downlink if a selective telemetry downlink scheme is implemented.

The SOC will also acquire all spacecraft data from the MOC, including telemetry and auxiliary files, and make them available to the Instrument Teams. Low latency data telemetry will be processed at the SOC, using PI provided software, in order to distribute this data set to all Instrument Teams as soon as possible so it can be used to support the planning process. Data processing at the SOC will be limited to auxiliary and low latency data production.

The Instrument Teams will process their telemetry into uncalibrated and calibrated data that they will deposit in the SOC archive in accordance with the data policy of the mission. All data processing and calibration software will also be deposited in the archive for long term preservation.

An archive will be kept at the SOC that will hold all data products from the mission, both of operational and scientific nature. The operational part of the archive is the posterity repository of all formal operational products exchanged across sites, but it is not treated as active working memory.

2.3.1 TM processing and Instrument Pipelines located within the SOC

For clarity, for Solar Orbiter the only science pipelines located at the SOC are those that process the low-latency data to a "quick-look", uncalibrated, not-for-publication quality products, as described above. The pipelines are provided by the instrument teams. These very minimal pipelines provide raw-imagery for pointing planning (in relation to solar features), and general "trending" situational awareness for assessing whether instruments are acquiring science data nominally[2], and for making decisions wrt selective data. Provision of true scientific products for loading into the Science Archive (as opposed to the SOMA) always comes from the Instrument Teams.

SOC will provide a web-based mechanism for instrument teams to easily view the low-latency "trending" information from any/all Solar Orbiter instruments, in order to facility inter-instrument understanding of the environment and the payload capabilities. SOC will use this environment themselves to maintain awareness of instrument operations and performance (although formal responsibility for checking instrument scientific health and tuning is with the instrument teams).

[2] Since normal ("bulk") science may be delayed by multiple months

2.4 SOC external interfaces

2.4.1 Interfaces SOC/MOC

The SOC will implement an interface with the MOC to exchange information about science operations planning, including payload operations and pointing requests, and constraints and planning rules checking. This interface will be controlled by the Planning Interface Document (PLID).

The SOC will also implement a second interface with the MOC to exchange mission data, including telemetry and auxiliary files. This interface will be controlled by the Data Disposition Interface Document (DDID).

The overall interface between SOC and MOC will be controlled by the Science Operations Interface Agreement (SOIA), which describes the responsibilities, operational implementation and interface procedures between the OGS and the SGS.

2.4.2 Interfaces SOC/Instrument Teams

The SOC will implement an interface with each of the Instrument Teams to exchange science operations planning information, including Instrument Operations Requests. Each Instrument Team will have a single point of contact with the SOC which will implement this interface. This same file-based interface will support the exchange of SOC-produced auxiliary files.

The SOC will also implement an interface with each of the Instrument Teams to exchange science data with the mission archive. Each Instrument Team will have a single point of contact with the SOC which will implement this interface.

SOC will implement a functionality that allows the IT retrieval of raw TM and MOC-products from the SOC. **Note** however that this is not the baseline mechanism for IT retrieval of these products. The recommendation is that the Instrument Teams access raw TM and MOC-produced auxiliary products **directly from the MOC** [SGS-RQR RID-18]. Rationale for this approach is

- Maintains the same interface as NECP and contingency/special operations
- Solar Orbiter bit-rates are much lower in comparison to many modern missions (EUCLID, GAIA etc), that the benefit of SOC "buffering" the IT TM requests is seen as negligible.
- Avoids the additional delay of passing data ESOC->ESAC before it is available to the ITs. (E.g. IT more-extensive monitoring of HK)
- MOC is 24/7 supported. SOC is not.

2.4.3 Interfaces SOC/Scientific Community

The SOC will implement an interfaces based on Internet Protocol to provide outside access to the mission archive, so the scientific community and the general public can gain access to the mission scientific data products.

These interfaces will be implemented at the mission archive, where both a graphical user interface and a machine interface will be available so the members of the scientific community can find and retrieve the data from the mission, and at the mission web site where information of a more general nature will be distributed to the public.

2.5 End-Users of the SGS

2.5.1 Internal users of the SOC

Instrument Operations Scientists: Evaluate science operations plans and analyse low latency data in order to support the planning process and assess whether planned observations were successfully carried out. They provide a human link between the individual instrument operations and the overall science goals.

Science Operations Engineer: Creates and validates science operations plans and transfers the operations requests to the MOC. He also uses the SOC to retrieve data from the MOC via EDDS

Operations Engineer: Supports the Science Operations Engineer in his role.

Archive Scientist: Receives science data from the Instrument Teams, and validates and archives all science data products.

2.5.2 SGS internal users which are external to the SOC

Project Scientist: Uses the SGS to support science coordination activities and to assess whether the scientific objectives of the mission are being met. He will obtain reports from the SOC on planning, low latency data analysis activities, changes to PI-supplied calibration data and software. TLM capture and ancillary data status shall be reported when such is anomalous.

Instrument Teams: They provide observation plans, planning inputs to the SOC. They use the SOC to obtain low-latency processed data, as well as auxiliary files they need to process their instrument telemetry. They will provide science data to the SOC for archiving.

2.5.3 External SGS users

MOC: They make planning inputs available to the SOC and, in turn, they receive from the SOC consolidated requests for payload operations

Science Community: They will obtain and exploit scientific and auxiliary data from the Solar Orbiter mission through the Solar Orbiter archive in the SOC. Note that a copy of the Solar Orbiter Archive shall be provided to NASA.

General Public: They will obtain information about the mission and its observations from the SOC through the Solar Orbiter website.

3 CONCEPT DRIVERS: REQUIREMENTS AND CONSTRAINTS

3.1 SIRD Requirements

The SOC will be developed and operated along the lines which will be described in the Science Implementation Plan (SIP) in response to the set of requirements specified in the Science Implementation Requirements Document (SIRD) [AD.01]. The most relevant requirements set in the SIRD which drive the science operations concept are summarized below.

The SOC will work with the Project Scientist and the SWT to prepare a top level activity plan. A baseline science operations plan will be established taking into account the scientific objectives of the mission and checking all known environmental, resource and mission constraints[3].

This plan is to be further refined by the SOWG, and implemented by the Instrument Teams with support from the SOC.

[3] These checks naturally being limited to the broad granularity at which the top-level activity plan is defined.

The requests for instrument science operations will be generated by the individual Instrument Teams and forwarded to the SOC on a periodic basis. The SOC collects these instrument operations requests and merges them in a single set of payload operation requests which is checked against the operational constraints and, once conflict free, is forwarded to the MOC. The MOC will be in charge of including these payload operations requests in the overall mission operations timeline to be uplinked periodically to the spacecraft.

The SOC will also track the triggering of on-board flags and the payload reaction to them so, at all times, the SOC will have knowledge of what observations have been run in each of the instruments.

The SOC, in coordination with the MOC, will keep track of each Instrument Team telemetry allocation and their usage of the Solid State Mass Memory (SSMM). Management of the SSMM will be also coordinated by the SOC, including the packet store and downlink priority allocation. The SOC will consolidate all selective telemetry download requests and forward them to the MOC.

In support of the science operations planning process, the SOC receives payload and auxiliary data from the MOC, including orbit and attitude information, event predictions, time correlation details and other mission specific data. An auxiliary data processing system will convert the auxiliary data into the formats used by the Instrument Teams and the scientific community. All telemetry will be made available to the Instrument Teams. Additionally a defined set of auxiliary data products will also be made available.

Beyond the instrument housekeeping checks that will be agreed with the MOC and which will be perform by the OGS upon reception of spacecraft telemetry, it is the responsibility of the Instrument Teams to monitor their housekeeping telemetry to verify the health and safety of their instruments. Likewise, it is their responsibility to monitor the quality of their scientific observations in order to adjust their instrument science operations accordingly.

The SOC also receives telemetry corresponding to low latency science data which is processed, using software provided by the PIs, into low latency data files to be distributed to all Instrument Teams and used to support both the planning process and the assessment of the health and performance of the instruments.

The SOC will also build a mission archive that will include all mission data received from the MOC or generated at the SOC. It will also archive operational products, in particular all those that are transmitted or received over the external interfaces of the SOC.

Science data produced by the Instrument Teams will also be deposited in the mission archive, together with the corresponding calibration software and files. Science data will be made available to the scientific community in accordance with the data policy of the mission. All data processing and calibration software will also be deposited in the archive for long term preservation.

The SOC will provide feedback to the Project Scientist so he can assess whether the scientific objectives of the mission addressed by the top level activity plan are being met.

3.2 Mission Profile

The mission baseline foresees that Solar Orbiter will be launched by NASA in July 2017. The mission will rely on a chemical propulsion system for manoeuver performance and on reaction wheels for pointing performance. A series of Gravity Assist Manoeuvers (GAM E1, V1, E2, V2... V6) with Venus and Earth will allow Solar Orbiter to reach its trajectory objectives of a 0.28 AU perihelion and an orbital inclination of up to 33° with respect to the ecliptic. A description of the spacecraft trajectory and mission phases can be found in the Consolidated Report on Mission Analysis (CReMA) [RD.02].

3.2.1 Mission Phases

The SIRD identifies the following project phases relevant to the SOC development and operations:

Development Phase:	From Kick Off to IOCR.
Operational Phase:	From IOCR to End of Mission.

Relationship between the above and other mission phases according to SIRD and CReMA is detailed below:

LEOP Launch and Early Operations Phase From launcher separation until completion of the launcher dispersion trajectory correction. Typically 7 days.

NECP Near Earth Commissioning Phase From the end-of-LEOP until the completion of the platform commissioning (ends with IOCR). Typical 90 days

CP Cruise Phase From the end-of-NECP until the planetary fly-by that puts the spacecraft into the science orbit. Typically ~1100 days, typically ends with GAM V2[4].

NMP Nominal Mission Phase 8 orbits, Typically ~4 years long, typically from GAM V2[5] to GAM V4.

EMP Extended Mission Phase Further 8 orbits. Typically ~3 years long, typically from GAM V4 to GAM V6.

[4] For July 2017 the final GAM of cruise is E2

[5] For July 2017 the final GAM of cruise is E2

In addition, there is one additional phase relevant to SOC operations:

POP Post Operations Phase Two years after the end of mission operations.

Almost all aspects of SOC functionality are required at the start of the SOC operational phase, since IS science operations are required during CP, and pointing and RS planning will be needed to support RS check-out windows. The specific functionality that may be delayed until NMP is selective downlink. This shall be supported only from start of NMP onwards.

3.2.2 Spacecraft orbit

The most relevant features of the spacecraft orbit for the operation of the SOC are:

- A maximum distance to the Sun of 1.15 AU for July 2017 (larger than 1.3 AU in other trajectories) reached during the early phase of the Cruise Phase, causing a cold thermal environment and severe power limitations.
- A first science orbit that follows the second Earth GAM (which marks the start of the Nominal Mission Phase) and that leads into the GAM V2[6].
- A 168 day long heliocentric orbit resonant with Venus inclined with respect to the ecliptic after GAM V2. The orbital period changes at each GAM where a change in orbit resonance with Venus is made. Typically the orbital period decreases through the mission (with the aphelion coming down nearer to the Venus orbit radius) – by-product of the GAMs increasing the inclination whilst maintaining perihelion low.

3.2.3 Instrument operations and Remote Science Windows.

All instruments will be commissioned during the NECP. After commissioning, the in-situ (IS) instruments will be continuously on and operating under near-nominal conditions[7]. The remote-sensing (RS) instruments however, are expected to undergo an extended phase of calibration and characterization during the CP, depending on specific requirements. They typically will be checked out for up to one week period every six months during the duration of this phase.

[6] For July 2017 trajectory. Other trajectories typical start the first science orbit at the GAM V2.

[7] IS operation is CP is “not to drive resources”. This means significant reduction in datarates compared to NMP, and possible periods of non or reduced operation due to power constraints.

Once in the Nominal Mission Phase, the IS instruments will operate nominally all the time, but the RS instruments acquire data during pre-defined periods called Remote Science Windows (RSW). The baseline mission calls for three 10-day long science windows per orbit located centered on the perihelion and on the points of largest solar latitude of the spacecraft. Although the mission design restricts RS operations to RSWs, the concept is more fuzzy in practise.

- Even when RS-instruments are not actively observing they may not be OFF.
  - If they remain in standby, they continue to consume power and generate HK (both at reduced level), and this resource usage has to be accounted.
  - PHI for example can perform its onboard processing of raw data outside of the RSW in which the raw data was acquired. This approach leads to higher power consumption than a standby-mode would (but may be advantageous in allowing more control of when the write to Spacewire occurs).
  - Some instruments have created annealing modes, that they desire to run outside of RSWs
- Feature-tracking RSWs require precursor imagery of the sun-disk in order to select the target feature. Sometimes this can be performed with Earth-based assets, but sometimes it will be necessary to perform this with EUI and PHI full-disk imagers in a short window prior to the RSW. This approach is called a "precursor window"
- Beyond the well-defined precursor concept, some instruments identify the need to perform calibration activities before and after science acquisition periods. Sometimes these calibrations require turn-around on ground. (It is arguable whether these calibrations necessarily occur outside the RSW, or as part of the instruments observing concept they belong as an activity within the RSW itself).
- Some RS instruments have advanced the idea that they could be allowed to operate in a synoptic way around the orbit.

Naturally this tendency of creep of RS operations beyond the RSWs can only be allowed to the extent that i) the SWT agrees it, and ii) it does not violate constraints like:

- Power
- Data
- EMC quietness requirement across the orbit
- Planning constraints
- Manpower assumptions of MOC and SOC

This particular arrangement for the science operations of the Solar Orbiter payload derives from the need to operate the whole payload, IS and RS instruments, together in order to address the scientific objectives of the mission, and the quite strict mission constraint on the overall telemetry downlink capacity available to the payload.

3.2.4 Ground station coverage

The baseline ground station coverage is three 8-hour passes per week during CP and daily 8-hour passes during NMP and EMP, measured by the length of telemetry dumps. The default ground station allocated to Solar Orbiter is Malargüe, therefore the passes will happen typically from late morning to early night in the SOC local time. In addition, there is a budget for 19 additional 8 hour passes with another 35m station for every orbit in the nominal mission phase.

3.3 Spacecraft and Mission Constraints

3.3.1 Data constraints

The spacecraft telemetry is returned via X-band. While the nominal telemetry downlink rate is of 150 kbps at 1 AU, the effective telemetry downlink rate is very dependent of the distance between the spacecraft and Earth and modelling it will be critical for successful science operations planning. The variation in effective telemetry rates between the most favourable and the worst orbital configuration is a factor of about 25. Moreover, the total telemetry volume that the mission can expect to return to Earth under realistic conditions is about 1.5 TBytes[8], according to preliminary analysis carried out by the SOC Team and contrasted with information provided by Astrium, the prime contractor.

Because of the limited telemetry downlink rate, the latency of the science data stored on the SSMM can be very long, up to close to the orbital period. Therefore, the management of the SSMM will be another critical task of the SOC. A priority scheme will be applied in order to downlink high priority data as fast as possible (i.e. low latency data), and selective telemetry downlink requests may have to be used for gaining access to specific periods of telemetry when solar or on-board events demand it. The SOC Team is leading a study analysing whether implementing a selective telemetry downlink scheme consistent with spacecraft resources is feasible.

Another constraint of the spacecraft is that, beyond SSMM packet store size and priority allocation, there is no technical mechanism on-board to enforce that the Instrument Teams do not exceed their telemetry allocation. Therefore, the complex interplay between packet store sizing and their prioritization has to be carefully monitored and controlled by the SOC. In practise the largest part of managing this resource is done apriori, by

- Involving a mission-level planning activity as part of the definition of the SAP
- Sizing the packets stores appropriately
- Communicating limits on the instrument TM generation in specific periods.

[8] This is approximately the the EID-A allocation per orbit multiplied by the number of orbits over NMP+EMP. Current analysis shows that some trajectories are marginal to met this.

Some limited aposteri control is possible though control of the downlink[9].

The total sizing of the SSMM (3x256 Gib) was designed to ensure that all science telemetry over one orbit can be stored, assuming the nominal telemetry data rate for each IS instrument, and that RS instruments operate during 30 days per orbit. However, Astrium and SOC analysis show that this is only possible with certain degree of optimization of the ground station passes. Therefore, the SOC will develop tools to optimize the scheduling of the ground stations, and its result will be forwarded to the MOC so it can be taken into account with negotiating with ESTRACK the ground station support to Solar Orbiter.

3.3.2 Power and thermal constraints

There are no power or thermal constraints identified so far that might affect the operations of the payload during any of the mission phases with the exception of the cold excursion to more than 1.3 AU at the beginning of the CP. During this period, the RS instruments will not operate, and the IS ones may need to suspend nominal operations.
Nonetheless SOC will model instrument power consumption by mode, so that the integrated instrument operations products can be checked against SC power constraint.

One important aspect of power for solar-orbiter is the supplied power available from the solar arrays. This is driven by

- The distance from the sun
- The cant angle that the arrays are driven to. This is turn is driven by
    - the power requirement
    - the temperature constraints on the array. At low sun-distance the arrays have to operate at higher incidence angles to avoid overheating.
    - the desire to limit the array degradation, by constraining the accumulated Equivalent Sun Hours. This means that higher angle of incidence are preferred.
    - TBC, the power that will be drawn. Excess power (beyond consumption) will dissipate as heat on the array. The extent to which this is a driver is unknown prior to SC-CDR.

The current concept assumes that the profile of SA cant angles follows directly from the sun-distance, and can be fixed, at the latest, at LTP.

[9] Often Solar Orbiter is generating TM many times faster than the downlink can bring it down. In these periods clearly directing the usage of the downlink offers limited control.

3.3.3 Orbit

It is expected that the spacecraft orbit will be well known in advance, therefore not impacting long term science operations planning. The payload operations will be restricted around orbital manoeuvers close to GAMs.
An updated orbit file can be expected after each GAM, but in practical terms its impact on planning is expected to be negligible. Unlike planetary missions, there is no short-period planetary orbit, and therefore there should be no need to reference mission-planning execution times to orbit event times like pericentre.

3.3.4 Pointing

The reference attitude of the spacecraft (SC) has the +X spacecraft axis orientated towards the sun centre (i.e. heat-shield and idealised imaging boresight orientated to the sun), and the +Z spacecraft axis orientated to the orbit normal. This reference attitude is to be used when no other pointing requirement is active.

Off-pointing
The spacecraft can nominally point the +X SC axis up to 1 degree away from the sun centre. The high-resolution telescopes have a Field of View (FOV) much smaller than the full disk, and so off-pointings can be a common feature of RS-windows, with the spacecraft being pointed to a specific part of the disk. Sometime these pointings may be simple and "geometric", e.g. disk-centre, solar south pole. On other occasions tracking a particular solar feature may be of interest. Solar features change over timescales similar to the duration of remote-sensing windows. Furthermore solar features exhibit a proper motion relative to averaged models of the differential rotation of the solar photosphere. These two aspects lead to the creation of a Very-Short-Term Planning (VSTP) mission-planning cycle which is concerned solely with target-selection and target-tracking for remote sensing windows.

> Target-selection: Choosing a specific feature to follow from those available on the visible part of the disk. (The type of feature to select and track having been defined already in SAP). Updating the pointing profile to point to this feature. Most-likely this is done with a full disk image from each of PHI and EUI.
>
> Target-tracking: Observing a particular feature as it moves across the visible disk and correcting the SC pointing profile for the proper motion.

Normally we expect that target-selection is done once in the precursor to an RS-window, and target-tracking thereafter. However some types of feature (e.g. active regions) can decay unexpectedly, and therefore a new target-selection may sometimes be necessary in the middle of a RS-window. This has consequences when planning the availability of full disk images.

To support the fine-pointing of the SC and updates of pointing requests during the VSTP cycle, a dedicated tool will be developed that visualizes recent science data, downloaded

with low latency from the SC, and enables the SOC to define the best pointing profile to e.g. track solar features on the disk, point to the solar limb or one of the solar poles over extended periods of time, etc.
Using off-pointings to build a raster for a high-resolution telescope may also be needed. Off-pointings may also be necessary outside of RS-windows, for example during instrument check-outs as way to establish flat-field calibrations.

Roll

Besides the off-pointing, the spacecraft can also roll around the +X axis. In general it is desirable to maintain the roll angle according to the reference attitude, however there are occasions where a change in roll angle is needed.

Communication Rolls: At some points in the mission the High Gain Antenna's (HGA) view of the Earth (when the SC is in the reference attitude) is intruded-on by some piece of the spacecraft. These intrusions do not follow a simple pattern, and may even occur inside remote-sensing windows. The potentially intruding parts of the spacecraft include the boom, either of the two southward RPW antennae, either solar array and parts of structure and heatshield around -Z. Additionally to these communication constraints there are HGA positions that would expose the HGA to thruster plumes, these positions also have to be excluded. When these intrusions occur it is necessary to roll the spacecraft to a non-default attitude that allows HGA communication (or forego communication in a kind-of planned artificial conjunction. This approach is operationally unattractive and would be applicable only on compelling science grounds).

The current Astrium analysis assumes that the minimum necessary roll is always performed – this maximises the time spent close to the default attitude (for which there is a requirement). However this also leads to a situation where there are extended periods where the spacecraft is regularly (once per day) adjusting the roll-angle (e.g. steering the earth around the edge of the obstructing body).

Scientifically it might be desirable to apply a different approach, rolling more aggressively (either roll-early/de-roll-late or simply roll to a higher angle) to keep the roll-angles stable for longer periods, for example in the case that the communication roll period intrudes into a remote-sensing window. Additionally the possibility to define a reference roll other than the orbit normal is being investigated.

Calibration Rolls: The Magnetometer instrument (MAG) requires a 12 x 360 degree roll rotation once per orbit as a calibration activity. There is no specific constraint on the part of the orbit in which this is done (other than it be EMC quiet) and thus these can be scheduled away from RSWs and passes. Other instruments may also require rolling, or a specific roll attitude for some special activities – for example rolls might be included with off-pointings as a way to obtain a flat-field calibration for RS-instruments, also RPW requests rolls close to Earth GAMs during Cruise to calibrate using radio signals created by auroral activity.

Roll planning in general: The SOC assumption is that all roll angles will be fixed in advance (probably via presentation of options by MOC Flight Dynamics/SOC and selection by the SOWG at the Long-Term Planning). Some awareness/planning of roll constraints is needed even before LTP when building the SAP, since rolling can have science impact, whereas not rolling (when one should) affects comms. (And it would not be clever to book station scheduling through a period of time where subsequently one chooses not-to-roll – this is driving the need to consider roll angles prior to at mission-level). The need to consider roll constraints a long time in advance is not consider a problem, since the roll constraints can be determined directly from the foreseen trajectory (and reference roll attitude).
No modification of roll angles later than LTP is foreseen.

Alignment

Within the scope of pointing, another important topic is alignment. All the remote-sensing instruments having high-resolution cameras (PHI, EUI, SPICE) have a FOV of the order of 16 x 16 arcmins3]. These FOVs are co-aligned with good accuracy on-ground, but in-flight effects (e.g. gravity release, thermo-elastic effects etc.) can cause mis-alignments up to 2 arcmin (inter-alignment error),and 3.5 arcmin (Absolute Pointing Error). Note that these figures are the requirements on the platform, and instrument-internal effects could contribute to greater misalignments. When planning pointing, the SOC will make use of a best-known alignment for whichever telescope is prime. This will be important for feature-tracking, where it is important to maintain the centre of the feature of interest near the middle of the appropriate FOV. It may be appropriate as well to maintain alignment parameters for fictitious FOVs corresponding to the union/overlap of two or more real telescopes, for observations where the science is driven by common observation, rather than simply having one instrument prime.

Furthermore the instruments are able to operate utilising only a sub-field of their full detector (or reducing the scan-stepping in the case of SPICE). This can help them to reduce their data volume for example. Operationally the SOC expectation is that the instrument-teams will agree to operate such that subfields, when used, are always centred on the middle of the full detector (or on the middle of the scan-range for SPICE). This avoids the need to parse the detailed instrument commanding when planning pointing profiles (in other words only the alignment of the centre of the telescope needs to be compensated).

At the moment, no complicated modelling of alignment variation with solar distance, temperature, instrument mode nor any other factor is foreseen (i.e. only a static, but configurable, alignment per telescope is foreseen). Any alignment model defined now would be only a guess, and calibration opportunities in-flight may be limited. If, after sufficient number of orbits, patterns in the alignment variation can be discerned, they could be addressed then, either introducing the alignment model directly into software as an upgrade, or by periodic manual adjustment (between planning runs) of the appropriate alignment definition.

Pointing disturbances

The Solar Orbiter remote-sensing cameras rely on good attitude stability (Relative Pointing Error - RPE) during integration. There are various platform activities that can disturb this stability, including wheel off-loadings, Solar Array Drive Mechanism (SADM) stepping, HGA stepping. For the platform disturbances the idea is to fix these in the Planning Skeleton File (PSF), and have the instruments plan their integrations to avoid these periods. This approach appears reasonable because of the very strong data volume limitations that apply to the mission, meaning that the RS-instruments will not be acquiring images at full-cadence for extended periods. In other words, it's not hugely impacting to have to suspend imaging observations occasionally, if anyway the data volume constraints don't allow anything approaching continuous acquisition.

The most frequent platform disturbance is probably the HGA stepping (once every few hours during worst-case passes). Other platform disturbances will be "stacked" as far as possible into the windows of the HGA stepping (or other principle attitude disturbance) with the principle to minimize the total disturbance time (if not the total amplitude).

One special sort of pointing disturbance is the introduction of an updated pointing under VSTP. As with other platform disturbances these will identified in the skeleton and disturbance-sensitive instruments will have to plan around them (on the basis that any update window *could* potentially be used, and therefore they must assume that it will be). In order to get these properly identified in the FECS we expect that the periods needing VSTP pointing updates are explicit in the SAP.

Many instruments have internal mechanisms (doors, filter wheels, slit selection mechanisms etc.). It is possible that some of these may also perturb the RPE performance. The exact list of "attitude disturbers" will need to be determined during Near Earth Commissioning Phase (NECP) or Cruise Phase (CP). The baseline approach for planning here is to establish windows or rules in advance defining the times when disturbing actuations are allowed. For this approach to work it will be necessary to find a suitable compromise in window density, to simultaneously allow positioning of disturbance-free integration periods with opportunities for mechanism activation.

3.3.5 Cleanliness and HV

Certain instruments have identified constraints on their operations with respect to thruster firings, either due to cleanliness concerns or high-voltages. Planning of these will be handled step-wise as follows:

- At LTP, when SOOPs are being defined, the MOC Planning skeleton will be available (this identifies windows associated to every nominal thruster firing activity). The planning at LTP is not performed at the level of deconflicting individual operations, but at least the SOWG will be able to see that a particular SOOP has thruster firings running though it and it will be apparent that e.g. completely uninterrupted operations by a thruster-constrained instrument through this period is not feasible. The SOC plan a visual environment to guide the construction of the SOOPs, and it is foreseen that this environment would also display the relevant windows from within the skeleton.

- Start of MTP onwards. The planning skeleton is made available to the instrument teams. The instruments shall plan their operations in accordance with these windows.
- Also MTP onwards. As a double-check, the instrument-team commanding inputs at MTP and STP will be checked at SOC for compatibility with their stated thruster constraints.

These constraints will always be applied in the sense that a thruster-firing windows means that **any and all** thrusters may fire. There will be no attempt to distinguish specific thrusters linked to particular operations.

(Constraints on **non-nominal** thruster firings, e.g. autonomous off-loading, must of course be reacted to by onboard FDIR and are not covered in any mission-planning activity)

3.3.6 EMC-quiet

MAG and RPW are sensitive to noise sources arising from the spacecraft and payload. According to the EID-A 70% of the orbit should be EMC-quiet.

The SOC will identify particular operations as “EMC noisy”[10]. The plan for this list of operations is to include as a starting point

- All motor or valve actuations
- All power consumption changes over a certain threshold.

The list will be maintained/updated in-flight

- To remove items from the list that are shown to be EMC-quiet (we expect a significant reduction of events to be achieved during NECP, and more during Cruise)
- To add new items if and when particular operations are discovered to be EMC noisy.

As a general approach, similar to what is done for pointing disturbances, spacecraft noisy operations shall be “stacked” as far as possible (to minimize the noise duration, if not the

[10] in fact multiple categories of “EMC noisy” are foreseen, such that we can track independently e.g. things that affect RPW-only or MAG-only (or even other instruments in terms of general compatibility), or e.g. things that matter during MAG burst modes but not otherwise.

amplitude). Many spacecraft noisy events are also create attitude disturbances, so this stacking approach becomes doubly appropriate.

Then beyond this there are two **very different** ways this EMC noisy list is used in instrument planning

- For short, specific, limited operations where quietness is important. Here a window will be placed by SOC in the Enhanced FECS (E-FECS)[11] prior to instrument MTP. This window will mandate noise-free operations in this period, and will be placed essentially arbitrarily in the time outside of the known Spacecraft noise operations. Instruments will be constrained to plan their operations such that they avoid placing any noisy operation (from the list) within this noise-free window. A typical example use-case here would be to create a 1 hour window every 24 hours in which e.g. MAG could place its scheduled burst modes. Another would be the entirety of the MAG calibration roll activity. N.b. This approach is **nothing to do** with achieving the 70% figure. This is because the noise-free windows will be **highly** constraining for some instruments and it is unreasonable to restrict their operations in an up-front way using windows that occupy 70% of time. Furthermore it is not reasonable to decompose the 70% figure (which applies across the orbit) to apply to any given STP planning period.
- Across the orbit, the proportion of time that was noisy (according to the list) shall be accounted in a passive way and then subsequently reviewed. If it is found that the 70% is not being achieved, this will be brought to the attention of the SWT, and mitigation actions on future planning discussed and agreed[12].

3.4 Other external drivers to the SOC

3.4.1 Coordination with the MOC

All instrument operations until the end of the NECP (until the In Orbit Commissioning Review – IOCR) will be planned under the responsibility of the MOC. The Instrument Teams will be in direct communication with the MOC up until then.

All instrument operations after the start of the CP (after the IOCR) will be planned through the SOC. All routine mission operations, including payload operations, will be pre-planned and executed off-line. The SOC must respect the MOC deadlines for planning inputs. If direct commanding is required for any instrument operation, for example to diagnose or solve instrument anomalies, the Instrument Team will interface directly with the MOC.

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[11] The FECS is the planning skeleton that comes from MOC. The E-FECS is an expanded version built by SOC as an input to Instrument Team's medium-term-planning.

[12] What these mitigations may be depends profoundly on which operations are found to be noisy in-flight, thus it is not considered useful to try to design any automated way of controlling/mitigating this.

The RS instrument checkouts distributed throughout CP will be planned using the SOC science operations planning facilities. The Instrument Teams may use these opportunities to characterize their instruments to make the best possible use of the science windows during the NMP.

The SOC will review and coordinate the commissioning plans that the Instrument Teams will produce as part of their Instrument User Manual. These plans will be executed by the MOC during NECP.

The SOC will also coordinate the calibration and characterization plans of the RS instruments. However, these will be run during the RS checkout periods during the CP as part of the nominal process of science operations using the SOC infrastructure.

The MOC is also supporting the SOC in the elaboration of the SSMM, telemetry downlink and ground station pass optimization models required to assure optimal telemetry return from the mission.

In order for the RS instruments to determine their pointing for an upcoming science window, some very limited amount observations could be scheduled a few days before. These observations will be part of the low latency data sets and will be downlinked at a higher priority than the rest of the science data acquired by the payload. These are referred to as 'precursor observations'.

Although the MOC will model spacecraft resource usage and verify the non-violation of spacecraft constraints, the SOC is expected to provide conflict free plans. To minimize the MOC/SOC iteration cycle the SOC will maintain a copy of the MOC mission planning Rules and Constraints database at SOC for checking planning rules and constraints relevant to the planning of science operations[13]. The SOC will also maintain a separate database of any additional instrument constraints (probably science-based) affecting operations. No duplication of rules or constraints will exist across these two databases.

Science data produced by the instruments and transferred from their internal memory buffers to the SSMM will be modelled by the SOC and checked against actual usage in coordination with the MOC. Data downlink will also be modelled by the SOC based on bit rate information provided by the MOC.

Due to the limitation on Solar Orbiter total volume of telemetry downlink and to the high latency that science data will suffer because of the mission profile, the SOC in coordination with the MOC and with the participation of the Instrument Teams might implement a

[13] The adaptation of the standard SOC planning tool "EPS" to support ingestion of the MOC Rules and Constraints format is already foreseen by other missions, and thus not expected to be problematic.

scheme of selective telemetry downlink. This will be accomplished by managing the number and size of the SSMM packet stores and their associated priorities, and by issuing specific requests to the MOC for bound telemetry transfers (which specify packet acquisition start and end times) if required. This feature will also take care of downlinking the low latency data products at a suitable high priority so they are available promptly for processing at the SOC and immediate distribution to all Instrument Teams. Telemetry packets containing low latency data will be identified by specific APIDs, so they can be routed by the SSMM to a dedicated high priority packet store which will downlinked during the next ground station pass.

Instruments, mainly RS ones, will use different pointing strategies: pointing at specific fixed solar coordinates, tracking particular solar regions for an extended period, or executing rasters over a solar region. In order to implement solar region tracking, the Sun's differential rotation has to be taken into account. Pointing Requests that track rotation will contain a solar rotation rate[14] computed by the SOC. This rate will then be applied within the MOC to achieve the needed pointing behaviour. The SOC will request commissioning of this feature during the CP, taking advantage of the RS check out periods.

3.4.2 Coordination with the Instrument Teams

As mentioned already in the previous section (Coordination with the MOC), the SOC will review and coordinate the commissioning plans that the Instrument Teams will produce as part of their Instrument User Manual. These plans will be executed by the MOC during NECP.

The SOC will also coordinate the calibration and characterization plans of the RS instruments. However, these will be run during the RS checkout periods during the CP as part of the nominal process of science operations using the SOC infrastructure.

As a general rule, instruments on Solar Orbiter are capable of acquiring much larger data volumes than the ones feasible to downlink via telemetry (in some cases up to a factor of 2000). Therefore, strict science data selection and data compression is usually required and carried out on-board by the instruments themselves. RS instruments, in particular, may process science observations outside of the nominal science windows, transferring at a later time either a selected subset or derived products to the SSMM for downlink.

Moreover, due to the limited telemetry allocation, RS instruments may not carry science operations during the whole period corresponding to science windows.

[14] This is the solar rotation rate computed for a specific latitude. As a byproduct

In addition, and in order to be able to execute science operations completely off-line as required by the mission profile and still being able to respond to targets of opportunity defined by solar activity, the instruments have implemented on-board flag exchange mechanisms by which they alert the rest of the payload to a pre-arranged set of events detected by a running synoptic program. Other instruments may react to such flags by switching observing programs upon their reception. The information about payload reaction to flag-exchange is required by the SOC in order to keep track of science operations, SSMM resources allocation and telemetry downlink modelling.

Requests for instrument calibration operations may have high priority if these activities are to be done in coordination with other space or ground based assets, or using several instruments in the payload in a coordinated fashion.

Some IS instruments, for example MAG, might require quiet periods where activities from RS instruments are minimal. These will normally be scheduled outside of nominal science windows.

Instrument Teams shall produce Instrument Operations Requests in a timely manner to the SOC can consolidate them into conflict free Payload Operations Requests in time to meet the MOC planning cycle deadlines.

Also, when the whole payload is executing a coordinated observing plan driven by high level planning at the SWT or the SOWG, a campaign leader would have to be identified to support the SOC in the planning process, in particular with pointing determination, with the required relevant and timely scientific decisions. Alternatively, the SWT or SOWG may establish clear rules that the SOC scientists can follow without relying on external parties.

The SOC team has to coordinate with the Instrument Team on the definition of the low latency data set to assess whether these can actually be downlink to ground during the next ground station pass under every orbital geometrical condition.

Instrument Teams which produce low latency data shall deliver telemetry processing software to the SOC so the specific APIDs containing these data can be reformatted and processed into files for use with the planning system. [RD.5] provides guidelines on software standards and delivery mechanism for these elements.

Instrument Teams will provide science data products and software to the SOC for archiving and distribution in accordance with the mission data policy.

The Instrument Teams will also provide support to the SOC in the elaboration of instrument engineering models that can be used for resource prediction during the planning process.

3.4.3 Coordination with the Project Scientist

The Project Scientist shall approve payload operations plans by leading the SAP writing and through the LTP planning cycle (see 4.2.2).

The SOC will provide feedback to the Project Scientist so he can assess whether the scientific objectives of the mission addressed by the top level activity plan are being met.

The SOC will consult with the Project Scientists on all matters related to science and on all changes proposed to the baseline mission scenario.

3.5 Coordination with other ESA projects

Several opportunities for coordination with other projects have been identified:

- Re-use of parts of the science operations planning tool from Venus Express.
- Re-use of parts of BepiColumbo data-retrieval from OGS.
- Re-use of parts of the science archives of SOHO and Ulysses.

However, the SOC shall have enough resources not to be dependent on the success of the development of other projects for any of its critical functions required for meeting the scientific objectives of the mission.

3.6 Coordination with non-ESA projects

The scientific synergies between Solar Orbiter and NASA's Solar Probe Plus (SPP) are addressed in the Solar Orbiter Science Requirements Document [RD.01]. SPP baseline mission calls for an August 2018 launch and there might be requests for coordinated observations during Solar Orbiter CP starting at 15 months before NMP. At this stage, the RS payload on Solar Orbiter is nominally off-line at the time. At present, this potential collaboration is not driving any of the development, operational or staffing requirements of the SOC.

As part of the MOU on Solar Orbiter between ESA and NASA, ESA will provide a copy of the contents of the Solar Orbiter archive to NASA.

3.7 Lessons Learned

According to lessons learned from other mission in the Science Programme, the SOC will address the following issues:

Keep the planning cycles as short as possible to be able to react to targets of opportunity (i.e. solar activity variability).

To avoid unnecessary SOC/MOC iterations because of PORs violating planning rules or constraints, a single database, maintained by the MOC but with a copy located at the SOC will be used for checking against non-instrument specific constraints.

Data quality is to be monitored as soon as possible so instrument operations are modified quickly to minimize bad quality observations.

A common archive supporting both science operations and science data distribution will be implemented to have a single point of access to all mission data and avoid the maintenance of two different systems as science data will be made available to the scientific community since the start of the CP. This archive will also receive software for data processing and calibration for long term preservation.

The SOC will make specific resources available to maintain the Instrument Team interfaces over the long run, as the PI responsibilities may change from institution to institution and the make up and know how of the PI teams evolve as the mission ages.

4 DESCRIPTION OF CONCEPT

4.1 Concept Overview

As a result of the analysis of the SIRD requirements, the study of the mission profile and coordination carried out already with the Project Scientist, the Project Team (in particular, the Payload and the Avionics Team), the OGS, and the Instrument Teams themselves, the SOC Team has already identified several discrete components that are likely to be the building blocks of the Solar Orbiter SOC.

At the current time, this is a conceptual design, and will have to be refined and detailed during the next phase of the SOC development. Figure 2 depicts the main components of this concept.

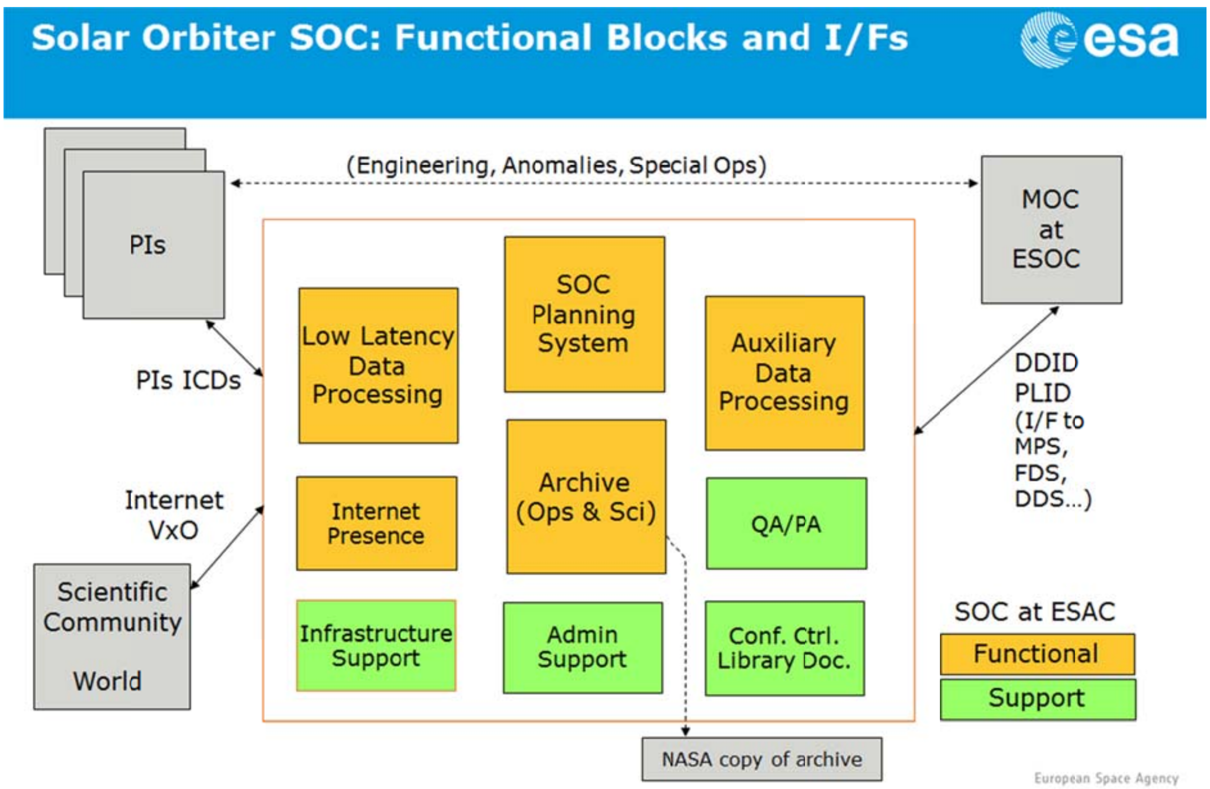

Figure 2. SOC Functional Blocks

4.2 The Planning Concept

Given the fact that instruments on Solar Orbiter are designed to study both solar physics and the heliosphere, and taking into consideration the constraints identified in the previous chapter, coordination planning science operations if of the essence in order to achieve the scientific objectives of the mission. This is particularly pressing for optimal usage of the science window opportunities for the RS instruments during the NMP, when the complexity of pre-planned science operations plans running off-line with the possibility of using on-board instrument generated flags to switch observing plans make an efficient use of the resources of the mission very challenging.

Therefore, the model for science operations planning being defined is that of an encounter-type mission, with as much advance planning as possible. The objective of the overall planning process described here is to refine progressively a very high level plan based on the top level scientific objectives of the mission as agreed by the SWT (described for now in the Solar Orbiter Definition Study Report [RD.04]), and considering the most important constraints from the mission profile, into a detailed science operations plan suitable for being converted into conflict free Payload Operations Requests used by the MOC to perform the actual commanding of the instruments all under the scientific oversight of the Project Scientist.

Solar Orbiter will reuse the three standard MOC/SOC planning cycles in use with other Solar System mission: Long Term Planning (LTP), Medium Term Planning (MTP) and Short Term Planning (STP) tailored to Solar Orbiter needs. These will be augmented by two additional levels of planning: An overall mission level one, to address the fact that TM downlink restrictions which extend further than a single orbit make impossible planning individual orbits separately, and a Very Short Term Planning (VSTP) cycle, needed in order to point to dynamic events that evolve in the Sun.

For the VSTP, the Project Scientist has specified a 3-day turnaround period based on studies that show that solar features drift because of proper motion in such a way that not updating pointing during a period longer that 3 days is roughly equivalent to pointing randomly at the Sun.

These planning cycles are all described in Table 1.

LTP	Covers a six month period, at a range of 6-12 months. This planning cycle is synchronised to the station-scheduling activity at ESOC.
MTP	Covers the same six month period as LTP. This is the cycle where resource allocations are fixed.
STP	This covers a weekly period (more across RSWs). This is the planning cycle that leads to instrument commanding that will be uploaded to the spacecraft.

Mission-level	A feature of the Solar Orbiter mission is very long latencies on return of data to ground, with associated heavy filling of the onboard Solid State Mass Memory (SSMM). For orbits with poor communications geometry, much of the data generated carries over into the subsequent orbit. Thus from a data-production point of view the orbits cannot be assessed in isolation. There has to be a global plan for data production and ground station usage, which takes account of the individual packet stores and their usage.
VSTP	This is a planning cycle related to pointing/PTR-update, driven by the following points • Solar features can be short-lived, so the "feature of interest" has to be chosen very close to the beginning of the RS-window. • Proper motion of features relative to the theoretical models of differential rotation, such that the HR telescopes may rapidly lose a feature without a quick feature-tracking loop. This activity is present only for those RS-windows where feature-tracking is present (i.e. it is not needed for so-called "geometric" observations The VSTP cycle also foresees a very limited set of instrument updates.

Table 1: Overview of Solar Orbiter Planning Cycles

At MTP and STP the planning cycle operates with fully representative commanding inputs from the instrument teams. At LTP (and indeed at mission-level) no such detailed products exist. The resource check of most concern is data production (i.e. the data-volumes routed over the SpaceWire link into SSMM), since this must be planned across longer periods than MTP. This leads to the idea of the IOR-placeholder. This is some simplistic representation of the instrument behaviour/state over time that can be derived from the long-term plans for science or, failing that, from the default allocations of the EID-A **Error! Reference source not found.**. The IOR-placeholder needs to carry adequate information to allow resource checking at LTP (and mission-level) planning.

Similarly the idea of a PTR-placeholder can also be defined. This serves a similar role, but for pointing. The cycles in which a PTR-placeholder is necessary can vary according to the type of remote-sensing window (e.g. solar feature-tracking has the firm pointing definition arriving later), therefore it does not necessarily follow exactly the same cycles as the IOR-placeholder.

Table 2 shows this placeholder concept by planning cycle. Also shown are the cycles at which PORs are generated by SOC, and the quality of the resource/allocation checks being performed.

	Mission-level	LTP	MTP	STP	VSTP
Pointing	SAP identifies • Pointing types by activity • Strategy for each comms roll	Pointing timeline	PTR for geometric pointing only	(same as MTP)	PTR
Instrument input	-	-	IOR	IOR	"delta-IOR"

Total Payload	SAP identifies • Coarse mode and TM allocations	Instrument timelines	POR	POR	“delta POR”
Quality of resource checks	*Crude*	*Intermediate*	*Detailed*	*Detailed*	-

Table 2: Overview of SOC inputs and outputs according to planning cycle

The following subsections describe each of the planning cycles in more detail. The concept was finalized in a dedicated workshop at ESOC in January 2013, and presented to the PIs at the SWT that took place in London in February 2013. Details of the concept that involve on-board data management matters needed to support it were discussed in a SOWG held at ESTEC in April 2013.

4.2.1 Mission Level Planning

The scope is the entire mission:

- The SWT allocates specific orbits to specific mission science objectives.
- Science objectives are classified by SWT into Core/Critical and Tentative.
- SWT/SOWG determines best locations for the RS windows, if not the baseline.
- Iterations with OGS on RS window location, given mission constraints with feedback to the SWT for plan modification if needed.
- Once RS window locations agreed, the SWT/SOWG produces draft science operations plan.
- The SOC with the support of Instrument Teams use instrument models to determine what level of resources (data, power, pointing) is required by the SWT/SOWG plan.
- The SOC executes its data return analysis and GS pass optimization to identify periods where additional GS passes are of critical importance to meet data return requirements. These typically span periods much longer than a single orbit because of telemetry constraints.
- The SOC feeds back resource estimates and GS requests to SWT/SOWG and OGS.
- Process iterated until level of planning detail is enough to determine S/C and GS resources, and available resources are sufficient for running the plan.
- The output feeds into the Science Activity Plan (SAP). Within the SAP there are two levels: CAP (Core Activity Plan) and Tentative Activity Plan (TAP)[15].

[15] This is important later when the plan has to accommodate the delta between the assumed and actual station allocation. Removal of TAP activities provides a clean path to achieve this.

This is not a one-off process. The overall plan has to be revised periodically as the shorter term planning cycles are executed. The output of this plan is required to proceed to the next level as it provides input which the OGS uses during negotiations of ESTRACK coverage. Specifically the mission-level planning needs to address

- Data allocations associated to science activities instrument-by-instrument
- Timing of the remote-sensing windows (since this can affect station planning)
- Broad strategy for comms rolls, where they occur (since this can affect station planning)

Figure 3 depicts the planning process in graphical form.

4.2.2 *Approval by Project Scientist*

SAP: The Science Activity Plan is a document produced by the Project Scientist with the SWT and supported by SOC. It defines the science goals of each orbit/RS-window.

- Instrument resource allocations, if different from baseline
- Pointing approach for each RS-window (i.e. whether the spacecraft shall point at e.g. the disk centre, or at a solar pole, or track a particular type of feature).

The SAP is the principal point at which the Project Scientist approves the science operations. We then consider that Project Scientist approval is needed for

- LTP, where non-critical science activities are descoped, or resources are reallocated between instruments or between planning phases.

Project scientist would also be informed for

- Contingencies that materially affect on-going operations

4.2.3 *Traceability of operations*

It is the responsibility of the Project Scientist to maintain any traceability of Science activities to Science Goals of the mission.

At the level of SOC, we foresee tracing of SAP activities as far as SOOP[16]s but no further (i.e. not into lower level products like IORs). Rationale for this is:

- Planning is by time-period. There is no autonomous scheduling of free-floating science activities to complicate the visibility of science goals
- Equally no SOC-level descoping of SOOPs/IORs is foreseen

[16] Solar Orbiter Observing Plan. This is the means of coordination between instrument's science planning, equivalent to the "JOPs" of SOHO. These are fundamental to planning at LTP.

- SOOPs will probably not have a simple traceability to science goals.
- IORs and SOOPs will not have a simple pass/fail relationship to science goals.
    - Any anomaly during operations will have to be assessed case-by-case for its impact on the science that was ongoing. Many types of anomaly will not significantly impact the overall science. Conversely events exist that would not be detected as anomalies during execution but which would nullify science (e.g. problem internal within PHI data-reduction, SSMM problem after operations leading to lost data)
    - Equally on solar orbiter it's entirely possible that the operations might run flawlessly, but the science goal still fail (e.g. if it is related to catching a flare and the sun does not oblige)

Rather we see the need for a post-operations review at the end of each orbit or the RSW phase of each orbit. This would be a telecon, or it could be part of the regular SWT meetings. Plausibly there are three levels to closing out science goals that would need to be traced via these reviews

- SAP activity executed onboard
- SAP activity bulk-science data arrives at PI-site and passes initial inspection
- Science products related to SAP activity arrive at the ESA Science Archive

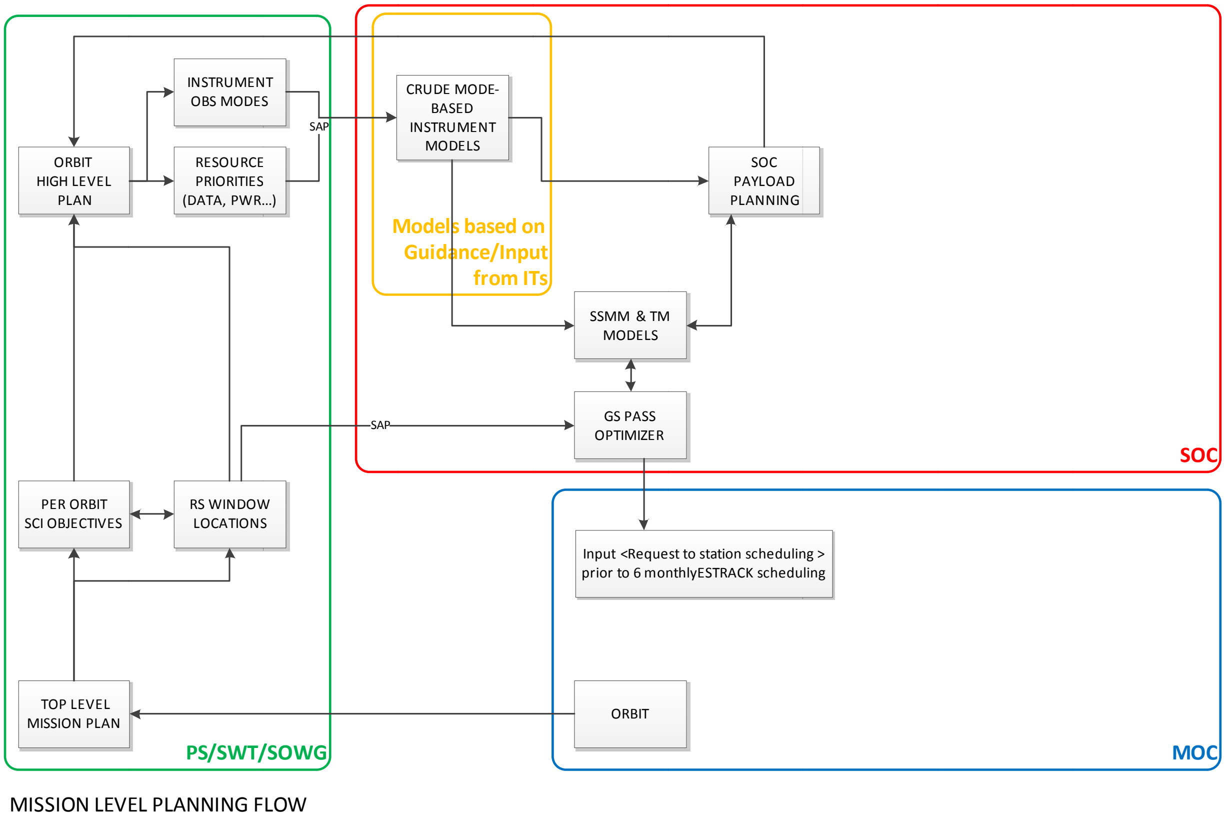

Figure 3. SOC Mission Level (top) Planning Cycle.

There is a final stage of "mission-level" planning not shown in the Figure 3 to keep the diagram clear. Like the final block this covers only the six month section of the plan linked to the station scheduling. This is the adjustment of the activity plan to fit the actually granted station schedule. This could be relatively simple, or complex depending on whether the SAP contains an adequate proportion of TAP activities to compensate the delta, and providing the rules for adjusting the TAP content are clear. It is this potential link to PS and SWT that places this step within the mission-level, rather than in LTP. The goal of this activity tuning is to control the state of the SSMM at the end of the six month period to match what is assumed in the mission-level plan. This avoids cascade replanning over the whole mission every six months.

4.2.4 Long Term Planning Cycle

The long term planning cycle is driven by the availability of a planning skeleton from MOC no sooner than six months before the start of the planning cycle being covered. This includes all known spacecraft activities and orbit events relevant for science planning including ground communications, manoeuvres and other spacecraft maintenance periods.

> In general it is expected that the MOC skeleton file marks firm times of operational events. Where appropriate however it can in some cases be used to indicate windows within which events have to be located, which may allow more scientific planning flexibility[17], the windows being converted to firm times in later planning. This will be addressed as the definition of planning and ICDs progresses.

The scope is one planning period, matched to the ESTRACK planning cycle.

- The SOWG refines the draft science operations plan and determines whether precursor observations are needed ahead of the remote science windows and any other calibration activity.
- The Instrument Teams detail their instrument operations.
- The SOC integrates all Instrument operations and checks against mission rules, constraints and resource estimates.
- The SOC feeds back planning information into the SOWG and the Instrument Teams.

All “coordination” aspects of the planning should be finalised in LTP, such that subsequent MTP planning is essentially instrument-by-instrument, within the timing already decided. Due to the centrality of the SOWG meeting for this process, we foresee a realtime planning tool that allows the display of instrument modes and pointing types over time. This tool is called “SOOP kitchen”.

This planning process with take place every six months, and has to be completed prior to 4 months before the start of the orbit which is being planned (to avoid a timing conflict with MTP).

Figure 4 shows the planning process in graphical form.

[17] In very general terms this may not be needed for many types of event, since the long orbit period of Solar Orbiter means that the precise hour at which an operational event is scheduled is probably not highly impacting for science, unlike planetary missions.

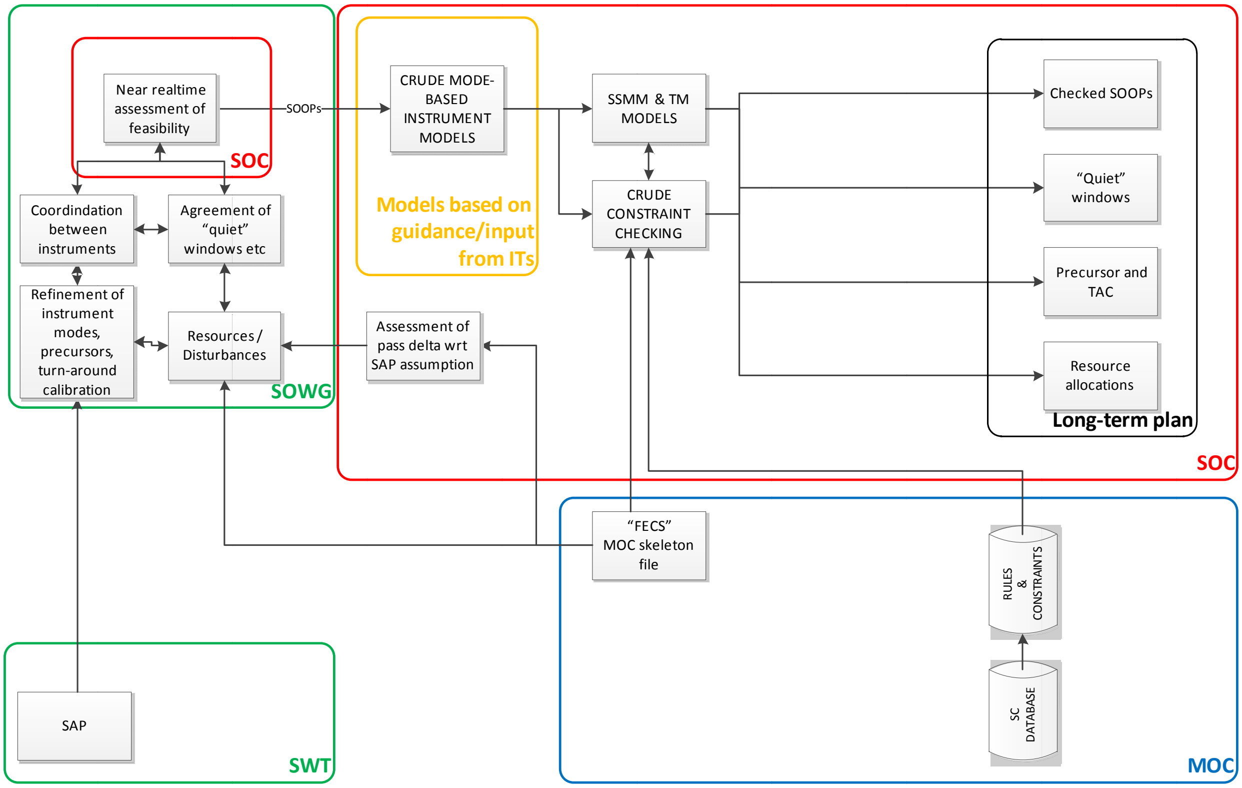

Figure 4. SOC Long Term Planning Cycle.

In the Figure 4 the process is shown starting from the SAP. This is in fact the station-schedule-adjusted SAP applicable to the six-months that comes from the mission-level planning. The hope is that that this tuning (to fit the station allocation) is more-or-less explicit from the SAP in terms of the identification of CAP and TAP.

4.2.5 *Medium Term Planning Cycle*

As part of the MOC medium term planning, the SOC will provide both Payload Operations Requests (PORs) and Pointing Requests (PTRs). This cycle determines the level of resources that will be used for the operations. Once the medium term planning is completed, the instrument operations might change during the short term planning cycle, but spacecraft resource allocation to the payload cannot be increased.

The pointing requests used during this cycle are the final ones, if they can be already determined. In general this means "geometric" pointings only (i.e. not feature-based).

Otherwise checks are made against an enumeration of the **type** of pointing foreseen. In any case, the pointing can be refined during the shorter planning cycles.

The MTP inputs will cover an entire orbit (n.b. this does not mean that this time-period is covered by a single file (for each type of input). The planning period at MTP covers a station-scheduling period, but we expect the granularity of most individual files to be less). It will be send by the SOC to the MOC 4 weeks ahead of the start of the planning period.

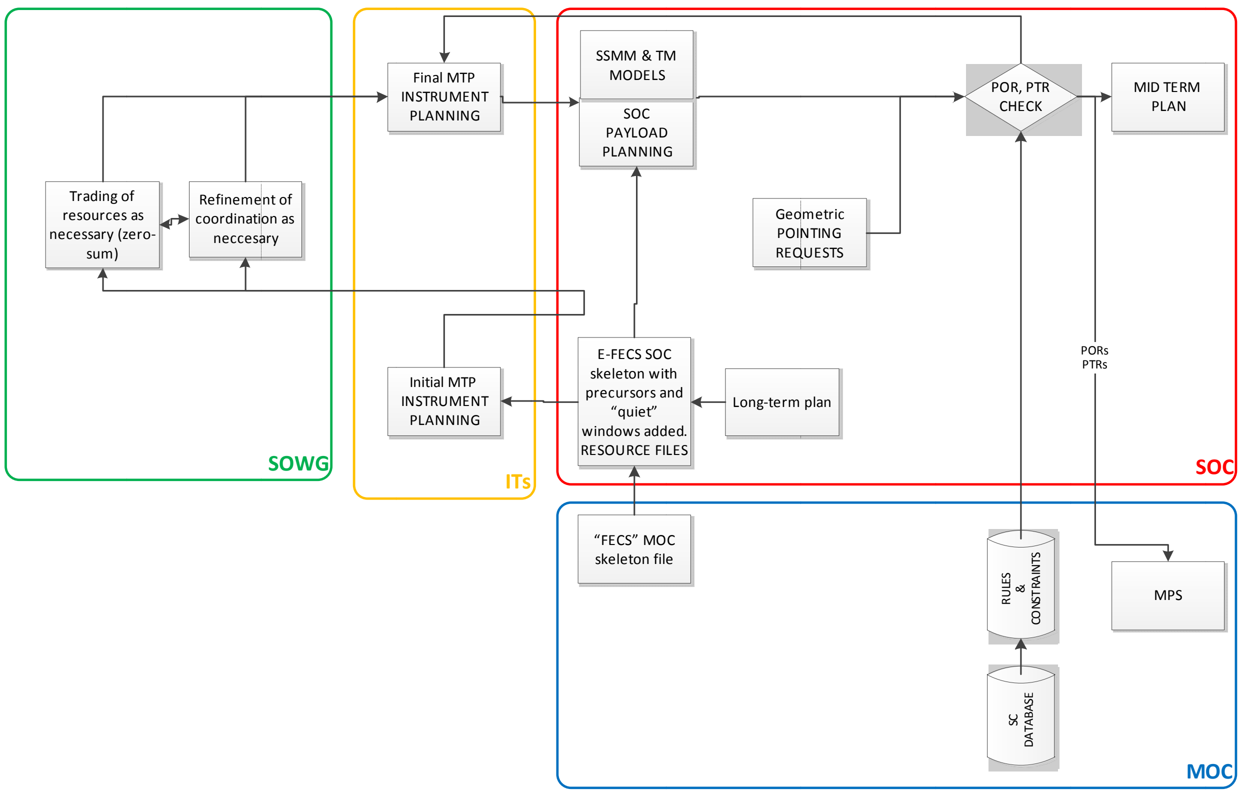

Figure 5. SOC Medium Term Planning Cycle.

TBC The MTP delivery SOC->MOC can also contain the MTP planned commanding of the downlink.

4.2.6 Short Term Planning Cycle

The final PORs will be sent at this time and will include the final command sequence parameters and cover one week of operations (more when an RSW is included), starting on a Saturday. These requests cannot exceed the resource enveloped established at the medium term planning cycle. At this time, the pointing requests may be refined as well. During a given week, the SOC shall send the input to the MOC on Tuesday for operations starting the following Saturday. No resource-impacting changes to the requests will be permitted after this time as the MOC will have to generate and verify the command loads and the attitude profile of the spacecraft in the meantime with adequate safety margins.

Figure 6 depicts this cycle.

Figure 6. SOC Short Term Planning Cycle.

The STP delivery SOC->MOC also contains the commanding of the downlink. In ideal conditions this simply follows the baseline created at MTP, but SOC can monitor the evolution of packet store status and adjust the downlink usage as needed. This adjustment is principally about “steering back to the plan” rather than making ad-hoc changes, since the use of the downlink is essentially zero-sum and lowering one store’s allocated downlink might not have an immediate effect, but could subsequently cause problems weeks into the future.

4.2.7 Very Short Term Planning Cycle

VSTP Pointing updates:
Solar features are not persistent over time, and also move with proper motion with respect to the standard differential rotation models. Therefore the pointing for solar-feature based science has to be determined and updated according to a rapid cycle involving ground. This cycle is designed specifically to update daily the pointing of the spacecraft, but the overall time that it takes from the downlink of low latency data, its analysis on ground, the pointing determination and the update of the actual pointing of the spacecraft is 3 days.

It will not be exercised in every Remote Science Window, and on those where is used it may be used only on certain dates and not in others.

VSTP instrument commanding updates:
Additional an extremely limited provision for instrument operations updates is allowed. This is included because of the identified need for certain instruments to respond to calibrations results made in the representative thermal/temporal environment of the science observations. The list of allowed VSTP sequences will be agreed in advance with SOC and MOC. It is expected that (empty) VSTP slots have already been identified in the STP IOR (this ensures protection against MTL overloading for example). Additionally constraints on Instrument VSTP commanding include:

- Addition of commanding only, no deletion (and delivered VSTP IOR is only the delta)
- No resource-impacting commanding
- Non-criticality in case the VSTP IOR does not get onboard (e.g. station failure)

See Figure 7 below for a graphical depiction of the planning flow.

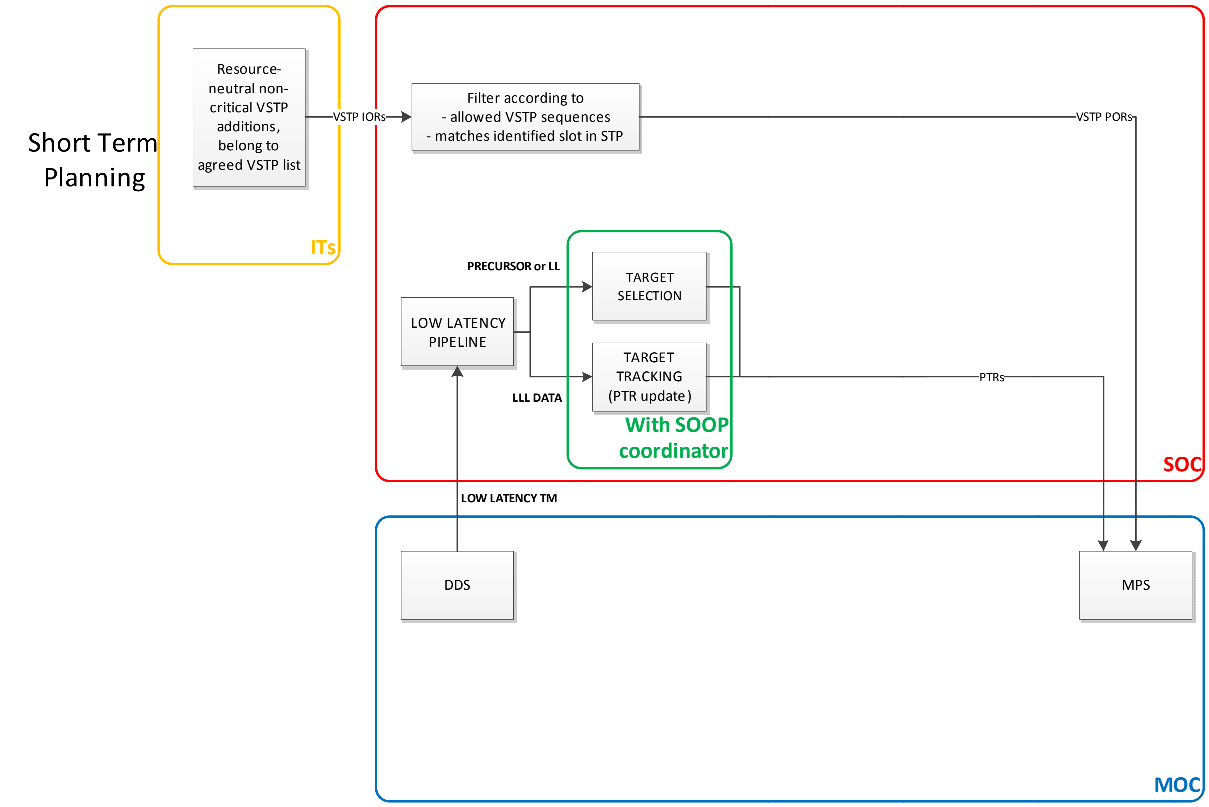

Figure 7. SOC Very Short Term Planning Cycle.

4.2.8 How the planning phases fit together

Previous sections have described each planning phase in some detail. This section is trying to show how the planning flows through the various phases.

It is important to appreciate that each phase is a refinement of previous phases. The planning can therefore be considered analogous to house construction, in that an architecture of the overall construction/mission is put in place first (i.e. the SAP) and design (planning) proceeds by incrementally refining the details.

Thus

- The top-levels of planning (LTP and especially mission-level) only represent a crude overview of the foreseen operations. These phases are not representing the fine details of operations nor constraint checking such details.

- There is no point where free-floating science operations are algorithmically assigned to time-slots[18].
- If an earlier phase (e.g. Mission-level - the SAP) has significantly underestimated the resources needed for a particular science goal, then compromises will often be necessary. Some non-critical aspect of the foreseen science can be descoped (e.g. remove non-critical science activity, or a more graduated solution like cadence reduction). If this is unacceptable resources can be moved from one instrument to another. Sometimes data resources can be moved from the next planning period to the current (but this is effectively a type of descoping).

Figure 8 below is showing how the planning cycles fit together.

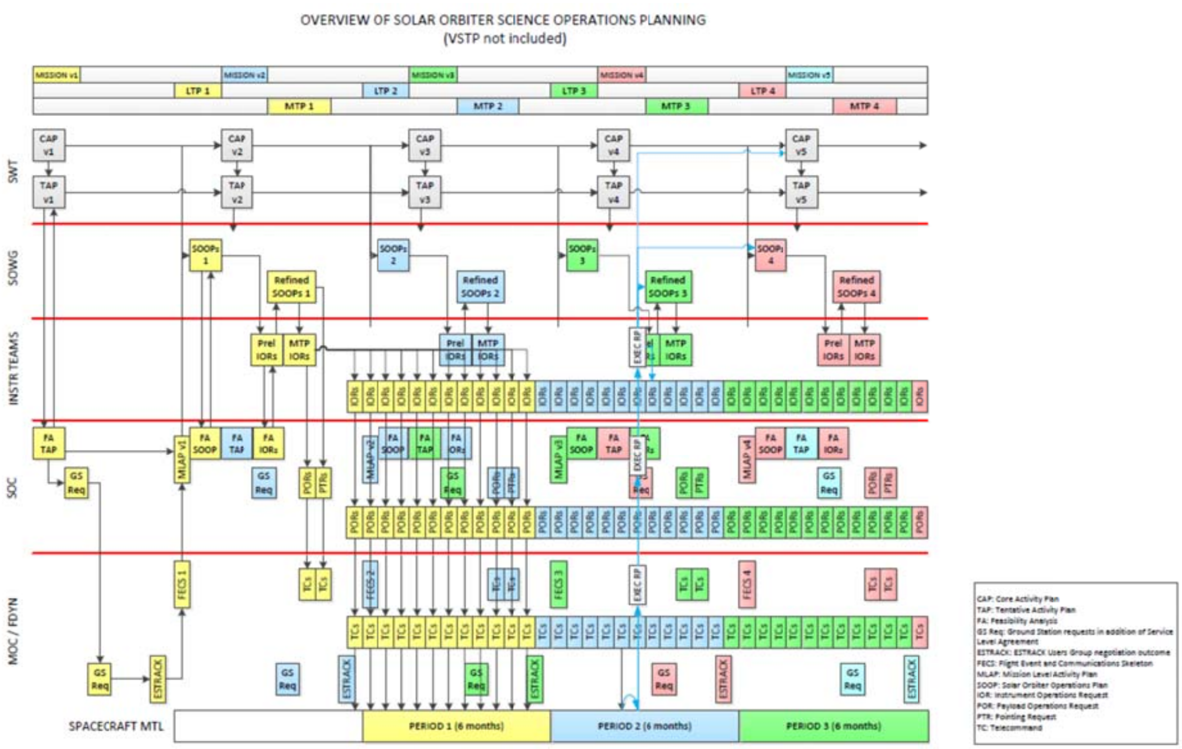

Figure 8, Overview of planning phase timings

Mission-level planning

Decisions made:

[18] I.e. no Herschel/Bepi-like planning.
The only aspect of planning that has any similarity here is the provisional positioning of the extra ground station passes at mission-level planning

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- Science goals of each orbit
- Crude modes of each instrument
- Crude data allocations per instrument per orbit
- Firm position of RSWs
- Pointing types applicable within each RSW. (N.b. **especially** important is the identification of RSW periods within which VSTP pointing update capability is needed. This is because "PTR sync-points" need to be defined, probably as part of the FECS creation at the beginning of LTP. These sync-points are needed such that FD know where they may need to accommodate a PTR update, but also so that the instrument teams can plan around the potential pointing disturbance that occurs here.)
- Firm roll strategy defined for comms blockages in standard attitude

Constraint checks:

- Long-term modelling of SSMM stores and downlink
    - Covering **critical** science ops only without extra pass scheduling
    - Covering **full** science ops including extra passes[19]
- Crude check of power ignoring short-term behaviours, and based on pre-FECS idea of available power

As input into subsequent stages (every six months):

- Produce requested station profile, as input into ESTRACK scheduling
- Tune Activities (principally TAP) to fit the actually granted station schedule

Long-term planning

Decisions made:

- More detailed modes of each instrument over time[20], including inter-instrument team coordination
- Needs for precursors and turn-around calibration identified
- Detailed slots for "special pointings" (rasters, PHI/EUI flatfields, etc.) agreed
- Firm configuration of low-latency data agreed[21]
- Firm approach for IIC trigger approach defined

[19] The feasibility of this two level SSMM/downlink modelling at mission level remains to be seen. On one hand it provides a powerful way of handling the uncertainty of how much of the ideal extra pass distribution will actually be granted via ESTRACK scheduling. On the other hand, if the SAP routine assumes EID-A levels of data to support the **critical** science then planning without the extra passes simply won't work.
[20] At the level of behaviour ~day-by-day, rather than ~minute-by-minute.
[21] At least as far as coordination needs and VSTP are concerned.

- Agreement of EMC "quiet windows" placement, if any
- Roll plan finalised (both comms rolls and calibration rolls)

Constraint checks:

- Power checks based on FECS and better defined mode periods, but still ignoring short-term behaviours
- Data checks based on better defined mode periods and detailed instrument input
- Crude "human eye check" of FECS events for impact on science goals (attitude disturbances, EMC noise)[22]
- SOC check that necessary low-latency data for pointing planning is available (if feature-tracking for example)
- SOC definition of TM production flexibility over time[23]

Medium-term planning

Decisions made:

- Detailed instrument commanding time-lines (IORs) built for the first time

Constraint checks:

- Power checks now based on IORs
- Data checks now based on IORs
- Detailed checks of compatibilities with e.g. foreseen pointing types, with the agreed EMC quiet windows.[24]

Short-term planning

Decisions made:

- IORs refined based on current knowledge (instrument state, environment)
- IORs refined to adapt for actual data production relative to TM production flexibility defined in MTP. Practically speaking this is where an instrument team might realise that they have to disable burst mode responses, or reduce cadence, e.g. if their actual TM production is starting to exceed the planning assumption.
- IORs include empty "VSTP windows" to indicate where VSTP commanding can occur.

Constraint checks:

- As for MTP

[22] Checked in the sense of "there will be X periods here with attitude disturbance which you will have to plan around later, ok?"
[23] This final stage of LTP is actually preparing an input needed for MTP.
[24] Unlike the LTP check these are hard constraint checks that can lead to rejection of an IOR.

VSTP planning

Decisions made:

- Instrument VSTP delta-IORs created if needed
- Feature-related target selection/target tracking performed by SOC with SOOP coordinator

Constraint checks:

- Only that instrument delta-IORs use allowed VSTP sequence calls and fall within declared VSTP update windows

4.2.9 Contingency Recovery Concept

Following the discussion of the mission-planning cycles it is worth to address the approach for mission-planning aspects of contingency recovery.

For Solar Orbiter two basic principles apply:

- Continue the planned observation for the benefit of the still-operating instruments
- Following isolation/recovery, always come back to (i.e. re-enter) the existing plan.

These principles can be adapted for both instrument and platform contingencies. For **instrument contingency** the former bullet applies at system-level and the later bullet applies to the instrument-in-contingency. For **platform-level contingency** only the later bullet applies.

The rationale for these principles is described here:

- Continue the planned observation for the benefit of the still-operating instruments. *The spacecraft operates as a shared platform for the 10 instruments, thus a contingency on one instrument does not justify abandoning a pointing profile or observing plan. Furthermore the comparatively infrequent RS-windows are positioned according to particular orbital configurations, so observing operations cannot be arbitrarily shifted in response to instrument unavailability.*
- Following isolation/recovery, always come back to (i.e. re-enter) the existing plan. *A quicker recovery to nominal operations is achieved by using an existing plan, whereas trying to re-optimise mission-planning for the contingency at hand can lead to delays in restarting science ops. Furthermore the superposition of the time-pressure to restart science and the novel planning can be dangerous. Replanning aspects can also act as a distraction to individuals who should be focussed solely on the critical isolation and recovery phase.*

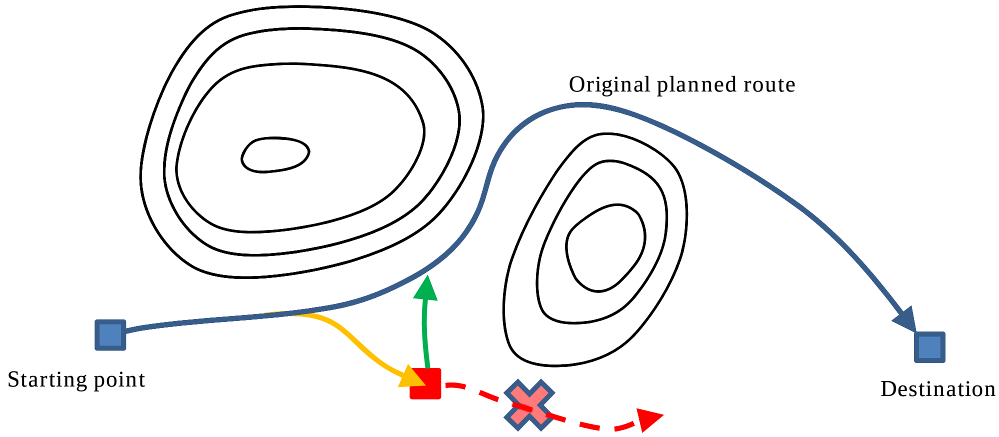

Figure 9, Hiking analogy to contingency recovery

After the successful recovery of the originally planned science operations, improvements in the future planned operations in the light of the contingency can still potentially be made, or investigated. But this now takes place in the context of normal short-term planning, or at higher-level if the impact justifies it – the most severe contingencies could potentially lead to a revision of the SAP where subsequent orbits are reassigned to allow a second attempt at an affected science activity. This planning (whether at STP, MTP, LTP or SAP level) is free of the time-pressure of the period with interrupted science.

The details of the re-entry into planned timeline need refinement and discussion with the instrument teams as part of normal operations design process. However there is a conceptual aspect that is useful to discuss, namely **timeline re-entry** points.

One normal feature of a contingency is that the affected instrument will stop executing onboard timeline commands directed to it. For instruments with complex timelines it may not be appropriate or safe to subsequently (after recovery) restart the timeline of instructions at any arbitrary time. That is, the timeline may assume that the instrument is in a state consistent with previous timeline commanding which, during a recovery, is not the case. Some very simple instruments, with little or on timeline commanding, may not have any constraint here, but complex instruments with multiple configurations (and maybe mechanisms as well) probably do have constraints.

There are various ways this can be handled, but the baseline for Solar Orbiter is that the granularity of the files delivered for instrument commanding (IORs) reflect the internally self-contained operations. In other words, the beginning of a new IOR file marks a safe "re-entry point" to the MTL. This file granularity is maintained through the SOC processing and delivery to MOC. These approach applies only to instruments needing a controlled re-entry to the MTL. More simple instruments would document their lack of MTL constraint in their CRPs and use an arbitrary IOR granularity, like e.g. 1 day.

Another conceptual point to note is commanding related to **redundant elements**. The recovery from contingency might include the decision to operate using a redundant element. In general we expect that the use of a redundant unit/element does not require any change in the timeline commanding. There is an OIRD requirement (REC-12) to this effect. If exceptions exist, they may delay recovery, since a re-planning (or maybe translation) of the prepared timeline would be necessary.

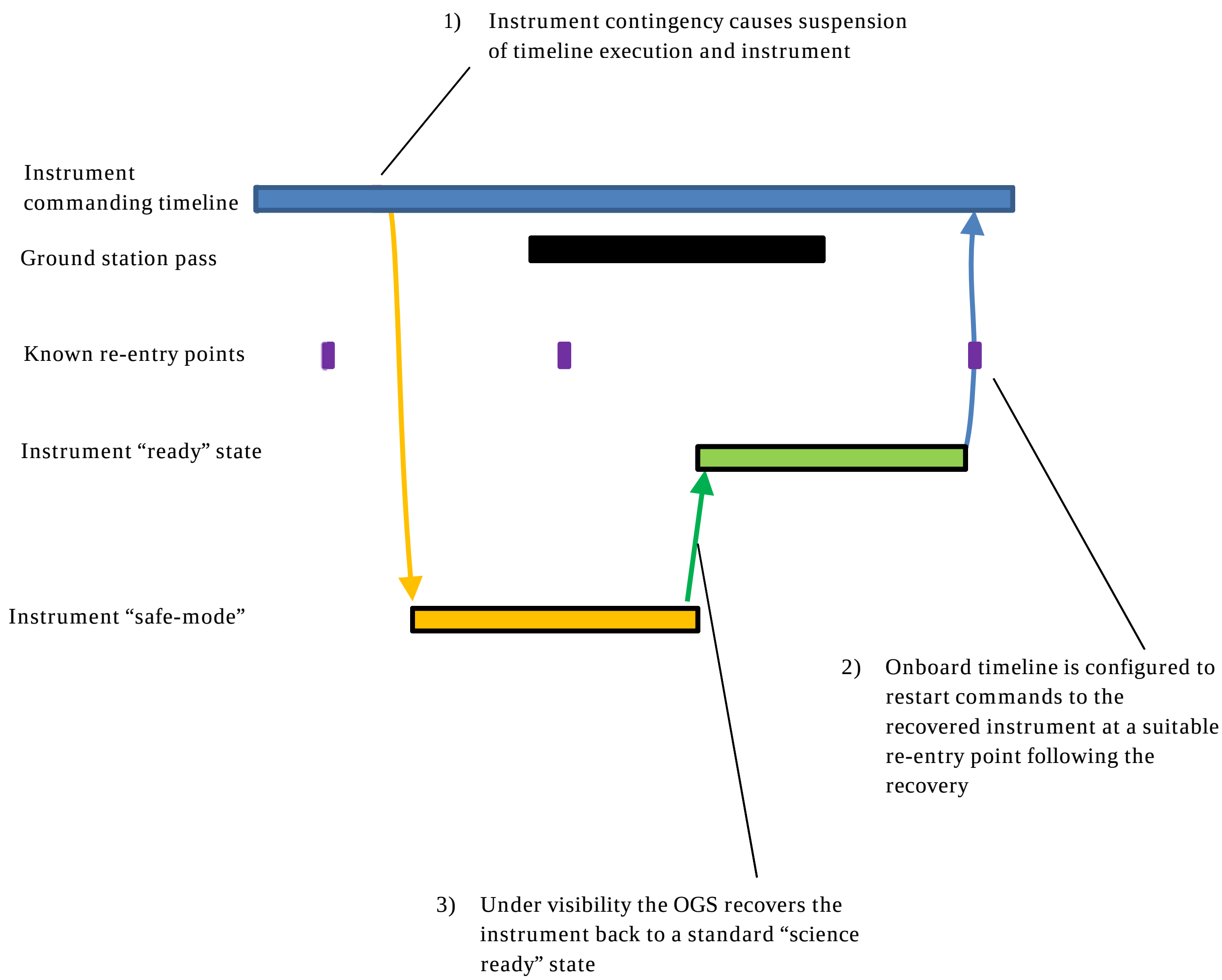

Figure 10, Illustration of re-entry points as a step in recovery of science operations

- Re-entry points should occur at least once a day.
- Re-entry points positioned close to the start of a pass are sub-optimal, since in most cases they have expired by the time any recovery is complete.