TECHNICAL PROPOSAL

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2 Statement of the problem

2.1 Context of the proposed research

The ultimate performances of a large class of astronomical instruments, telescopes, interferometers, coronagraphs, etc… are broadly dictated by the size of their optics, the capabilities of their focal plane instruments (e.g. spectroscopy) and of their detectors. Progress requires larger and larger instruments, and those presently in space are limited by the launcher's capacity. The present situation prevents the implementation in space of advanced, high-performance concepts such as large telescopes, large base interferometers, and large base stellar and solar coronagraphs.

To circumvent these constraints, a new concept has recently emerged consisting in distributing the instrument functions over several spacecrafts in a "formation flying" (FF) configuration. To be precise, formation flying means two or more satellites whose positions and orientations are mutually controlled and permanently assessed, so that the distributed payload over these satellites is equivalent to a very large dimension, single instrument in space. FF is now considered to be the most promising and effective approach to deploy the forthcoming generation of very large instruments in space. ESA is taking a leading role in this technology and has proposed an ambitious program starting with a demonstration mission PROBA-3 and culminating with DARWIN, an interferometer aimed at the search of terrestrial exoplanets orbiting nearby stars within their habitable zone. Figure 2.1 illustrates the progressive steps toward this goal, including other FF missions.

The solar corona is considered to be a laboratory of fundamental physical processes with extreme conditions common to solar and astrophysical plasmas physics. But studying the solar corona goes far beyond these theoretical questions as it ultimately aims at predicting those magnetic eruptions that affect Earth and its environment through geomagnetic storms, solar energetic particle (SEP) events, and radiative impact on the upper atmosphere, a field known as "Space Weather". The advent of formation flying heralds a new era of coronal studies as it will allow deploying giant coronagraphs in space capable of continuously observing the inner corona down to the solar limb under the conditions of natural eclipses – a goal impossible with present space and ground-based instruments. A forerunner instrument known as ASPIICS standing for "*Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire*" has already been studied during these past years (see references), and has been selected as the possible payload for ESA's PROBA-3 formation Flying demonstration mission.

There is now a wide consensus in the solar community that giant FF coronagraphs coupled with new, advanced focal plane capabilities allowing the determination of the physical properties of the coronal plasma and its magnetic field represents the next frontier. This is well illustrated by the recent announcement of opportunity issued by ESA for its Cosmic Vision program. Three missions based on this approach were proposed, COMPASS, DYNAMICCS, and HIRISE, all having in common the implementation of a FF coronagraph with advanced science capabilities aimed in particular at tackling the challenging question of measuring the coronal magnetic field. HIRISE was highly rated by ESA's Solar System Working Group, and although not finally selected because of insufficient maturity, recommendations were issued to pursue definition studies for a future re-submission.

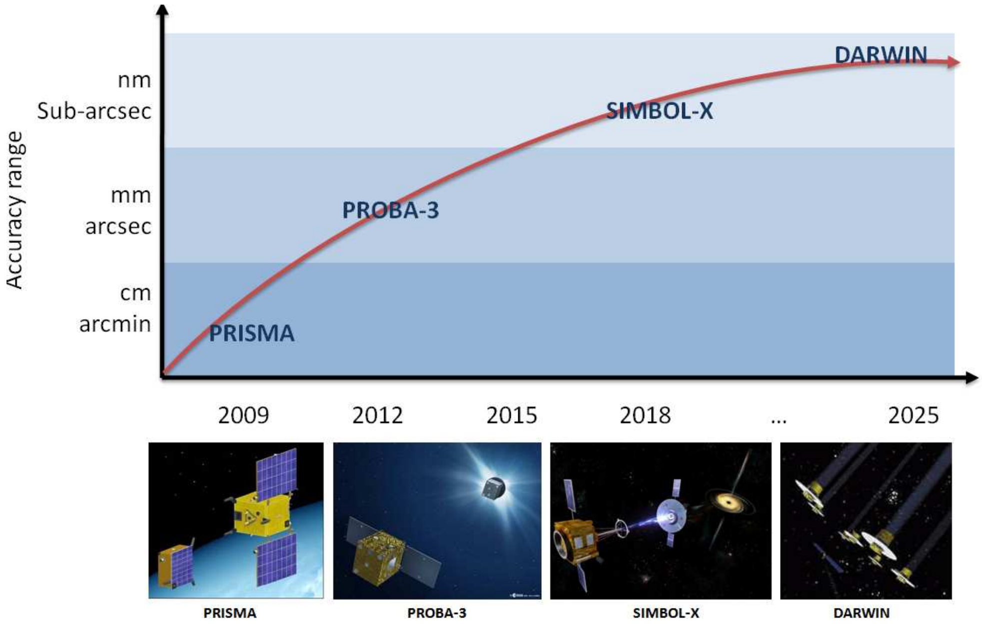

Figure 2.1 - Roadmap for the development of formation flying missions in Europe. Note that SIMBOL-X mission has been recently cancelled by CNES.

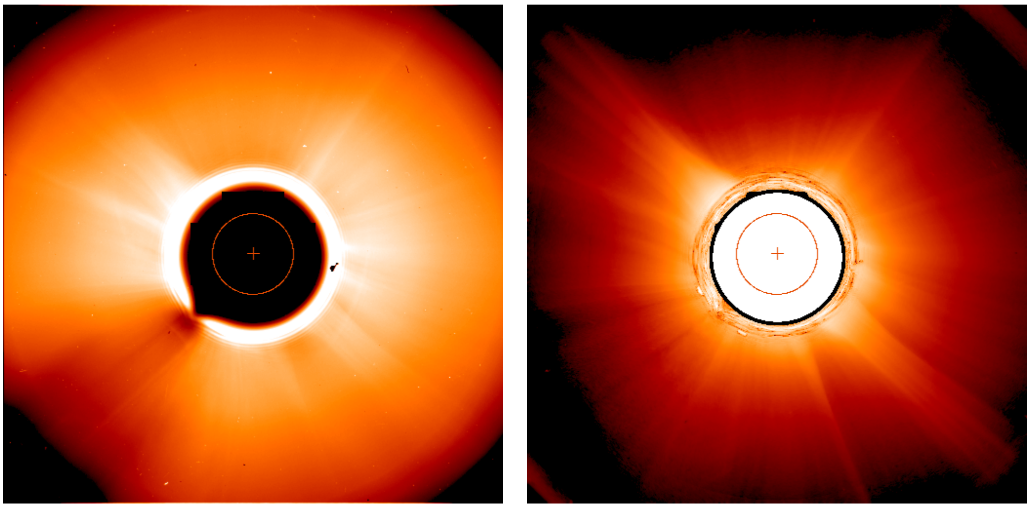

Figure 2.2 - Example of an image of the corona obtained with the LASCO/C2 coronagraph aboard SOHO. Left: raw image showing the bright diffraction ring surrounding the inner occulter. Right: the same image with the background stray light and corona subtracted, thus revealing the coronal plasma features.

The purpose of the present STARTIGER proposal is precisely to proceed with this new generation of formation flying solar coronagraphs incorporating the most sophisticated capabilities to operate diagnostics measurements in the solar corona in a unified, coordinated and progressive approach. Two parallel developments will concentrate on the most challenging aspects with structured objectives:

- The “Formation Flight metrology study” will address the crucial question of the alignment and pointing in space of long instruments (> 100 m) with an accuracy of a few arcsec.
- The “coronagraph study” will address the questions of implementing new optical designs allowing large apertures, of the reduction of stray light both external (occulter) and internal, and of advanced focal plane instrumentation and detector.

A first demonstrator will allow the validation of the optical concept of the coronagraph with its specific alignment and pointing subsystems, and is directly relevant to the very success of the PROBA-3 mission. A second demonstrator will validate one enhanced science capability among several that will be studied, and is directly relevant to the preparation of the Cosmic Vision generation of solar coronagraphs.

2.2 Status of the technology

Imaging the solar corona from space using so-called externally-occulted coronagraphs started some 40 years ago, and has culminated with the SOHO/LASCO and STEREO/SECCHI instruments both being still in operation. They represent a first generation of instruments with modest performances resulting from their limited size (typically of the order of 1m), their limited aperture (at best a few cm), and lack of sophisticated diagnostic capabilities (however see below the case of LASCO-C1). External occultation consists in placing a circular occulter (the “artificial moon”) in front of the optical aperture so as to block direct sunlight and realize an artificial eclipse. The negative impact of the occulter is to introduce a variable cat-eye effect (or vignetting) in the field-of-view (FOV) which seriously degrades the spatial resolution in the inner part where it is the most desirable because of the small scales of the coronal structures. Simple geometric considerations show that the imaging performances are linearly driven by the distance D between the occulter and the optical pupil. This is also the case of the instrumental stray light which results, not from direct sunlight since it is blocked, but from the still bright diffraction fringe surrounding the occulter (it should be kept in mind that the radiance of the corona is typically 10^{-6} that of the Sun in its inner part, and rapidly falls off with radial distance to 10^{-10} at 3 solar radii, R_{sun}). Here again, the energy coming from this fringe and collected by the pupil decreases linearly as D increases. The best externally-occulted coronagraph presently in orbit, SOHO/LASCO-C2 (D = 75 cm, pupil diameter = 2 cm) detects the corona down to about 2.2 R_{sun} (measured from the centre of the Sun, see Figure 2.2), has a spatial resolution as given in Figure 2.3, and has an average level of instrumental stray light of a few 10^{-11}, excluding the fringe surrounding the occulter. Attempts to decrease the inner limit to about 1.5 R_{sun} on STEREO/SECCHI/COR-2 have resulted in a huge increase of stray light. While it can be subtracted, the associated photon noise remains, and irremediably buries the low contrast coronal structures. In practice, the images are only useful beyond 4 R_{sun}.

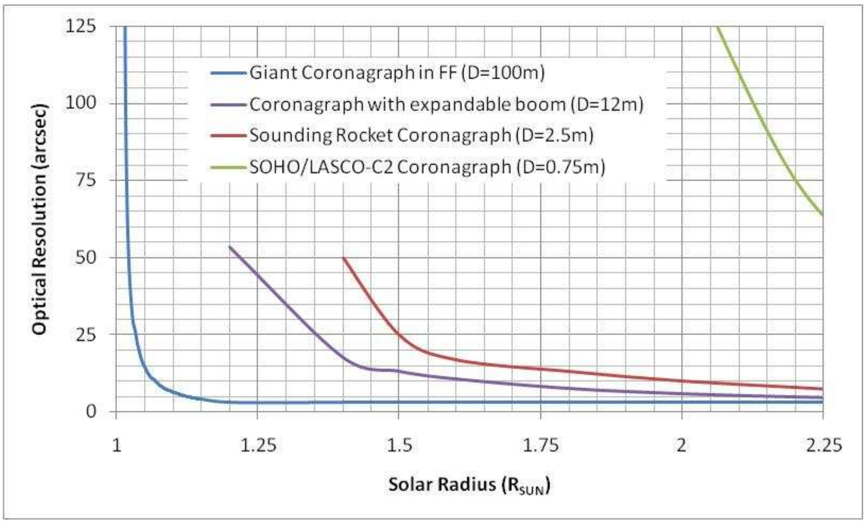

Figure 2.3 - Spatial resolution of various coronagraphs as a function of distance from the centre of the Sun. Note the vignetting effect which prevents observing the corona down to $1.25R_{SUN}$ except in the FF coronagraph.

The diagnostic capabilities of these externally-occulted coronagraphs are limited to measuring the linear polarization of the corona in order to separate the polarized plasma “K” corona from the unpolarized “F” dust corona and stray light, and to generate 2-dimensional maps of the electron density. The implemented methods are further rather primitive: a set of polarizers oriented at different angles or a rotating half-wave plate.

The SOHO/LASCO-C1 internally-occulted coronagraph was equipped with a scanning Fabry-Perot interferometer aimed at analyzing the profiles of several coronal emission lines (CEL) in an effort to initiate diagnostic studies (temperature, velocity, turbulence of the coronal plasma). The lack of maturity of such a complex subsystem led to major difficulties in its in-flight adjustment, and it irremediably break down when SOHO was temporarily lost. Highly successful diagnostic measurements were and still are performed in the ultra-violet (UV) with the SOHO/UVCS instrument. It is however a coronal spectrograph whose FOV is limited to its entrance slit as projected onto the sky. The slit has to be radially displaced and the whole instrument rotated to cover the whole corona, an operation which takes about one day, far too long compared to the temporal evolution of many coronal structures (minutes to hours).

2.3 The need for progress

The shortcomings in our present capabilities to investigate the solar corona as summarized above clearly delineate the areas where progress must be made, in order of priority:

- Develop a new generation of “giant” externally-occulted coronagraphs with D > 100 m capable of imaging the corona down to the solar limb with the best spatial resolution (at least a few arcsec), with the highest possible contrast, and at high temporal cadence (down to a few seconds).

- Develop new coronagraphs with significantly larger optical aperture sizes, up to 30-40 cm in diameter. This requires switching from the present refractive designs to reflective (mirror) designs – possibly three-mirror anastigmat - while preserving low levels of stray light.
- Develop 3-dimensional diagnostic capabilities so as to characterize the properties of the coronal plasma (density, temperature, velocity, turbulence) and measure the coronal magnetic field (presently unknown except in a few bright regions).

2.4 Factors preventing progress

The different factors which control the performance of externally-occulted coronagraphs have been discussed in Section 2.2. They are logically those which presently prevent progress.

- **The distance D between the occulter and the optical aperture of the coronagraph**. It must be considerably increased (at least 100 m) so as to reach conditions close to a natural eclipse in terms of low stray light and spatial resolution (no vignetting).
- **The size of the optical aperture**. It must also be increased (to 30-40 cm) for two reasons:
  - improve the spatial resolution so that it is ultimately limited by the pixel size, and
  - increase the collected signal so as to perform spectroscopic (diagnostic) observations. This second aspect is of further paramount importance in the UV where the coronal flux decreases with decreasing wavelength.
- **The lack of high performance, 3-dimensional diagnostic capabilities**. The present techniques of measuring polarization are too primitive, and 3-dimensional spectroscopic capabilities have yet to be demonstrated for coronal observations, especially in the UV.

As we will make progress on these three fronts, new problems will arise that will have to be addressed concurrently.

- Coping with **the full range coronal radiance** (typically a factor 10^4). The vignetting ("cat-eye") effect which seriously affects spatial resolution of present coronagraphs has the positive effect of compensating the strong gradient of the radiance of the corona, thus reducing the dynamics of the signal reaching the detector (roughly a factor 10). As this effect will be removed by increasing D, the detector will now have to cope with a dynamics of at least 10^4. Detectors with smart exposure control/reading, individually tuned for each pixel, would be a suitable solution to consider.
- **Designing new external occulters**. On present externally-occulted coronagraphs, the occulters have diameters of a few centimeters allowing sophisticated design of their edge so as to reduce their diffraction (for instance on SOHO/LASCO-C2, a multi thread cone obtained by diamond machining). The new generation of FF coronagraphs will have much larger external occulters, at least 1.5 m in diameter whose design has to be completely reconsidered taking into account the standard requirement of low diffraction AND the practical implementation on a satellite for which they will constitute the larger part.

2.5 Indications of the targeted applications

An important application is the development of the formation flight technique for scientific applications. The ESA demonstration program PROBA-3 with its foreseen coronagraphic payload will be the first scientific application to benefit from the proposed program. This will pave the way for other more demanding FF applications, culminating with the Darwin mission to study exoplanets. We emphasize once again that there exists a strong demand from the astrophysical community for the FF capability of deploying very large instruments in space. Five proposals requiring a FF orbital system were submitted in response to the recent ESA AO for the first round of its Cosmic Vision program, three involving a solar coronagraph. The metrology methods developed for formation flying could as well be applicable to large-scale rigid structures to be deployed in space in the future.

The development of compact telescopes with large apertures and low level of stray light is of wide spread interest not only in astronomy but also in remote sensing applications.

The proposed study of advanced instrumentation (such as 3D polarization and spectroscopy) is not restricted to the solar corona but also of general interest to many astrophysical domains. In fact the problematic is common to the observation of extended sources ranging from the Sun to galaxies.

The quest for a scientific CMOS sensor is today still in its infancy, but various developments are being pursued. Several groups have now demonstrated back-illuminated CMOS sensors that achieve quantum efficiencies in line with their CCD counterparts. The linear dynamic range of today’s best CMOS sensors is still considerably less than a CCD. However, several approaches to overcoming the problem are being investigated including the concept of pixels that deliberately behave in a non-linear fashion. We are also aware of efforts at the Jet Propulsion Laboratory (USA) to develop sensors that allow individual pixels to have varying exposure times.

2.6 Analysis of potential competing solutions or teams pursuing the same solution

The first significant effort to increase the distance D between the occulter and the optical aperture came from a joint team from the Naval Research Laboratory (Washington) and the Center for Astrophysics (Harvard). They proposed to use an expandable boom to deploy the occulter at about 12 m from the optical pupil. This system would have been implemented on an orbiting S/C part of the SENTINELS fleet, a program which is still on hold. Such a system offers a very partial solution to the need for progress, and little possibility of further development (boom cannot expand to very large distances), and no application in other fields of astrophysics.

Several technical aspects of advanced instrumentation such as Liquid Crystal Variable Retarder (LCVR) technology for both polarimeters and Fabry-Perot interferometers are in various stages of development and implementation for diverse solar applications. The most advanced are those used in ground-based facilities. They are now being developed for balloon borne (e.g., SUNRISE) and space (e.g., ESA’s Solar Orbiter) applications. We see those developments as more complementary than competing with what we are proposing. The specific application of these techniques to the particular case of a coronagraph imposes considering specific constraints (large field-of-view, large contrast, high stray light rejection) which justify our proposed program.

The quest for a scientific CMOS sensor is today still in its infancy, but various developments are being pursued. Several research groups have now demonstrated back-illuminated CMOS sensors that achieve quantum efficiencies in line with their CCD counterparts. We are aware of efforts at the Jet Propulsion Laboratory (USA) to develop sensors that allow individual pixels to have varying exposure times.

3 Goals and Deliverables

The proposed STARTIGER program will address the general question of implementing large-based scientific instrumentation in space and specifically, the challenge of developing, testing and validating the concept of a new generation externally-occulted solar coronagraph operating in formation flying. In the proposed concept for the future PROBA-3 mission, the instrument is distributed over two platforms separated by about 150 m, and forming a giant externally-occulted coronagraph: the imaging part is hosted by one spacecraft and remains entirely protected from direct sunlight by remaining in the shadow of the external occulter hosted by the other spacecraft. This basic configuration corresponds to a "rigid" long base instrument, and in this case the formation can be considered as the instrument. Our study will focus on two main aspects:

- The coronagraph itself: optical designs allowing large apertures, reduction of stray light both external (occulter and S/C) and internal (instrument); and advanced focal plane instrumentation and detector.
- The formation flying metrology: concepts and demonstration of optical systems insuring the verification of alignment and pointing of the instrument with the required accuracy (typically a few arcsec).

3.1 Coronagraph (WP 2000)

The next generation of space externally-occulted coronagraphs with large apertures (diameters of up to 50 cm are being considered) can no longer rely on a refractive optical concept, and we must switch to a reflective design. The proposed solution favors a three-mirror anastigmat telescope (TMA) because of its high image quality over a large field-of-view and compactness.

Stray light (SL) is a major concern in coronagraphs, especially when it comes to observing the corona close to the solar limb, a prime objective of FF instruments. The main source of stray light is the diffraction by the edge of the external occulter. Sophisticated solutions to reduce the SL level such as a triple disk (SOHO/LASCO-C3), a muti-thread cone (LASCO-C2) or a serrated disk will be difficult to implement on very large larger occulters having basically the size of the hosting satellite (a diameter of 1.5 m in the case of PROBA 3). The proposed solution favors a short truncated polished cone - whose laboratory performances are promising – because of its stiffness. Note that in case of FF, on top of the edge of the EO, the complete side facing the coronagraph is also critical and has also to be considered as potential source of SL. The last source of SL is diffraction and scattering in the instrument itself (optical components and structure). The proposed solution combines super-polished mirrors with improved baffling design (a critical aspect of three-mirror telescopes since the beam is folded two times).

Previous solar coronagraphs remained limited by their rather primitive diagnostic capabilities. In order to expand the science capabilities of the next generation of FF coronagraphs, we will investigate several solutions to carry out high performance polarization and spectroscopic measurements aimed at operating diagnostics in the solar corona. We will focus on liquid crystals (LC) based devices since they offer the following advantages:

- they are electro-optically modulated, hence no moving parts introducing either S/C attitude perturbation and/or optical path disturbances (optical axis changes, focus changes, …);
- they have large acceptance angle, hence they accept large field-of-views as required for the solar corona;

- they have a fast mode of operation (10-100 ms);
- They require low-voltage bias (<20 V) with little power consumption.

In addition, environmental tests (extreme vacuum and temperature conditions, irradiation by energetic particles) have shown no degradation in performances indicating that liquid crystal is sufficiently robust to survive in the space environment. Therefore, they have a clear advantage over existing mechanically rotated retarders and piezo-electrically tunable filters, and they can be implemented in polarimeters, tunable filters, and tunable Fabry-Perot interferometers. These potential applications will be investigated in the STARTIGER program.

With the advent of long base coronagraphs, the strong gradient of the radiance of the corona is no longer compensated by the vignetting created by the external occulter (EO), and the detector must cope with the full dynamics of the corona (at least a factor 10^4). Although a science grade CCD detector can basically handle this range, it is difficult to reach a sufficient signal-over-noise ratio in the outer faint corona without saturating the bright inner part in a single image. CMOS Active Pixel Sensors (APS) offer the possibility to address and control individually each pixel, and therefore to use varying exposure times depending upon the illumination level of each pixel. In addition, CMOS APS technology allows large-scale on-chip integration and low voltage operation thus offering the possibility of considerably more compact and lower power cameras than CCD systems.

3.2 Formation Flying metrology (WP 3000)

The basic configuration of the coronagraph corresponds to a "rigid", long base instrument, and the formation can be considered as the instrument. Classically an instrument has to be both correctly aligned (intrinsic to the instrument) and pointed (linked to the S/C capability). But aligning and pointing in space a 150 m long instrument with an accuracy of a few arcsec represent a considerable challenge. The peculiar configuration of the FF coronagraph imposes that the specifications be logically organized in the following order:

- Absolute pointing of the formation (i.e. pointing of the instrument);
- Relative pointing of the two spacecraft (i.e. alignment of the formation).

Note that this organization is in complete contrast to that usually applied in classical instruments and needs to be demonstrated.

While the satellite system will have its own metrology system to monitor the formation (RF communication, optical lateral sensors), the phase A study of the PROBA-3 mission has clearly established that the initial (and probably periodic) calibration of the satellites GNC systems must be provided by the scientific instrument itself. Two main actions will be carried out within the STARTIGER program:

- Identify, develop, test, and validate the alignment and pointing subsystems of the coronagraph.
- Test and validate the whole system in order to simulate the overall calibration and alignment process.

The **alignment of the instrument** must be performed through the coronagraph itself, and its verification can be achieved by quantifying the positioning of the occulter in the field-of-view of the coronagraph. The proposed solution, the “Occulter Position Sensor” (OPS) is based on several activable light sources on the rear side of the external occulter which are imaged by the coronagraph optics onto its detector.

The **absolute pointing of the formation** can be performed by verifying the centering of the optical pupil of the instrument in the shadow cone formed behind the occulting disc. The proposed solution, the “Shadow Position Sensor” (SPS), is based on measuring the penumbra around the entrance aperture of the coronagraph. Optimum pointing to the Sun is therefore achieved when the penumbra levels are balanced.

3.3 Deliverables

Two hardware demonstrators will be delivered with their associated GSE and control software:

1. A demonstrator of the instrument composed of two parts
    a. the coronagraph (TMA) with its metrology subsystem (SPS) for FF verification;
    b. the occulter at distances larger than 20m with an optical system simulating the shadowing (shadow and penumbra), and the OPS pointing subsystem.
2. A demonstrator of the Liquid Crystal Tunable Polarimeter

Reports (including analysis technical reports, compilation of lessons learnt during the STARTIGER phases, recommendations for future exercises) will also be provided by the team.

The complete list of deliverables is given section 9.5.

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4 Study Logic

The STARTIGER activity is a 6-month project structured around the following objectives:

- Formation Flying metrology study and demonstration:
    - Demonstrate individual performances of the metrology units (SPS, OPS) and of the Three Mirrors Anastigmat (TMA), for both pointing and alignment of the formation:
        - Validate concepts of each unit;
        - Verify individual performances of each unit;
    - Demonstrate the complete metrology logic and establish the practical overall procedure for controlling the whole instrument FF system;
    - Perform compatibility studies of the metrology units with future PROBA-3 implementation.
- Enhanced coronagraphic functions study and demonstration:
    - Analyze and optimize instrumental straylight analysis and optimization, both internal (science specifications) and external (science + FF specifications);
    - Demonstrate feasibility and performances of Liquid Crystal Tunable-filter Polarimeter (LCTP);
    - Optimize focal plane detector (e.g., smart APS detector);
    - Perform compatibility studies of the TMA, the external occulter, the LCTP and smart detectors focal plane with PROBA-3 implementation.

Figure 4.1 shows the study logic organized around the Formation Flying (FF) metrology and the Coronagraph instrument. These two high level tasks are then distributed among the two spacecrafts of the formation, the “Coronagraph S/C” and the “Occulter S/C”, and share some necessary equipment/demonstrator for their completion. In particular, the TMA is useful to the validation of the FF alignment task when coupled to the OPS (Occulter Position Sensor) and the SPS (Shadow Position Sensor), and to the validation of the FF pointing task when coupled to the EOS (External Occulter Simulator).

The Coronagraph Spacecraft demonstration relies on three demonstrators and two studies:

- the TMA Demonstrator
- the LCTP Polarizer Demonstrator
- the SPS Demonstrator
- the Focal Plane Study (advanced APS detector concept)
- the Stray Light Study

The Occulter Spacecraft demonstration relies on:

- the OPS Demonstrator
- the EOS Breadboard

The two benches and their demonstrators corresponding to the two spacecrafts are essential to carry the fundamental FF validation foreseen in this STARTIGER study: the Absolute Pointing and alignment tasks. The Absolute Pointing validation will establish the proper performances of the function simulating the solar pointing measurement from the EOS position (determined by the ASCS, the Altitude Spacecraft Simulator) using the SPS Demonstrator. The Alignment Validation will independently establish the performances of the function simulating the alignment of the two spacecrafts, by establishing the performances and range between the two spacecrafts benches, using the TMA Demonstrator precise information on the Coronagraph S/C bench and the position derived from the OPS Demonstrator on the Occulter S/C bench.

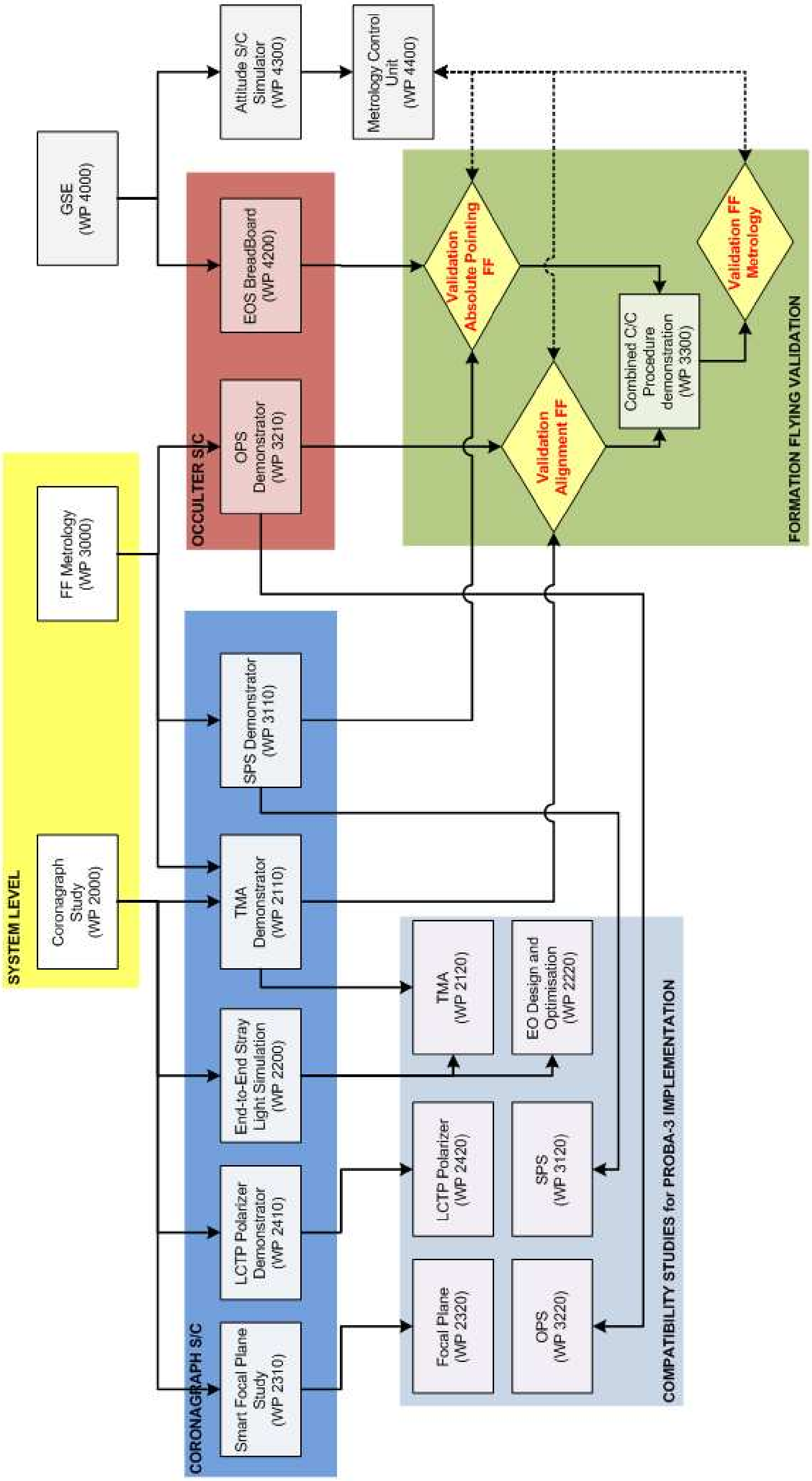

Figure 4.1 – Study Logic Diagram.

These two tasks, when completed, will provide the necessary information to elaborate a complete procedure of combined control-command Absolute Pointing and Alignment, starting from an arbitrary position. After its successful application on the demonstration benches, the procedure will be validated.

Note that, as evidenced on the chart, these tasks require Ground Support Equipments (GSE) to create the proper environment for the demonstration benches. In particular, the Altitude Spacecraft Simulator provides the required controlled pointing offset to the Occulter S/C bench in order to validate the FF Pointing function while the Metrology Control Unit allows the precise position measurements for both the FF Absolute Pointing and Alignment verification.

A priority level and an implementation phase in the work flow are associated to each task to be performed, compatible with the duration of the STARTIGER Study. This is summarized in the flow-chart presented on Figure 4.2. The two high level tasks are presented, FF Metrology and Coronagraph Study.

4.1 Priority Level 1

The FF Demonstrators (SPS, OPS and TMA) and the validation of the Absolute Pointing and Alignment of the Formation Flying assembly are Priority Level 1. These two essential validations are compatible with the STARTIGER First Implementation Phase (first 4 months) and their completion is mandatory.

The Control-Command procedure combining Absolute Pointing and Alignment, and its validation from an a priori arbitrary S/C alignment and pointing is the ultimate goal of the FF assembly demonstration. Its implementation takes place in the 2^{nd} phase (last 2 months) since it relies on the successful completion of the Absolute Pointing and Alignment validations.

The End-to-End Stray-Light Simulation which is part of the Coronagraph Study high level task, is also at Priority Level 1 since it is essential to the successful validation of reflective, three mirrors optical combination for ultimate, near-limb coronagraphic observations.

4.2 Priority Level 2

The two other tasks in the Coronagraph Study in the first implementation phase, which enhance the science throughput but without direct incidence on the FF demonstration: the LCTP (Liquid Crystal Tunable-filter Polarimeter) study and the smart APS detector study (Focal Plane Study), are both priority level 2. LCTPs constitute a key element to future multi-objectives science missions without the complexity and inherent risks (optical and mechanical) associated to classical mechanisms. APS detectors are promising to cope with the very large dynamics of coronal observations, in particular when observing from very near the solar limb to several solar radii, a new capability offered by what the FF concept of externally-occulted coronagraphs.

The three compatibility studies for the implementation of the SPS, the OPS, and the TMA on the PROBA-3 mission are also Priority Level 2. The first two studies, part of the FF Metrology high level tasks, are directly relevant to the very success of this FF demonstration mission. The third study (TMA) is relevant to coronagraph demonstration without being critical to the FF demonstration. Note that the End-to-End Stray-Light Simulation study is also an input to the TMA compatibility study since it will address stray light internal to the instrument.

4.3 Priority Level 3

The two compatibility studies for the possible implementation of the science enhancements, LCTP and smart detectors on the PROBA-3 or other future missions are Priority Level 3.

The compatibility study of the external occulter with the PROBA-3 “occulter” spacecraft is also Priority Level 3.

4.4 Summary

In summary, priority level 1 tasks are at the heart of the proposed STARTIGER study and, as such, are critical to its success and mandatory to complete. Priority 2 tasks will pave the way to the practical implementation of the studied FF systems to the PROBA-3 MISSION and to technical developments aimed at fostering the science return. Priority 3 tasks will bring these technical developments to the level of instrumental subsystems of widespread interest for not only future coronagraphs but also for many scientific instruments.

Overall, the study logic is organized so that the demonstrators, essential to the FF Metrology demonstration, are brought from an initial Technology Readiness Level (TRL) of 2 (or even 1 for the OPS and SPS) to breadboard demonstration in a relevant laboratory environment, i.e. to a TRL level of 4.

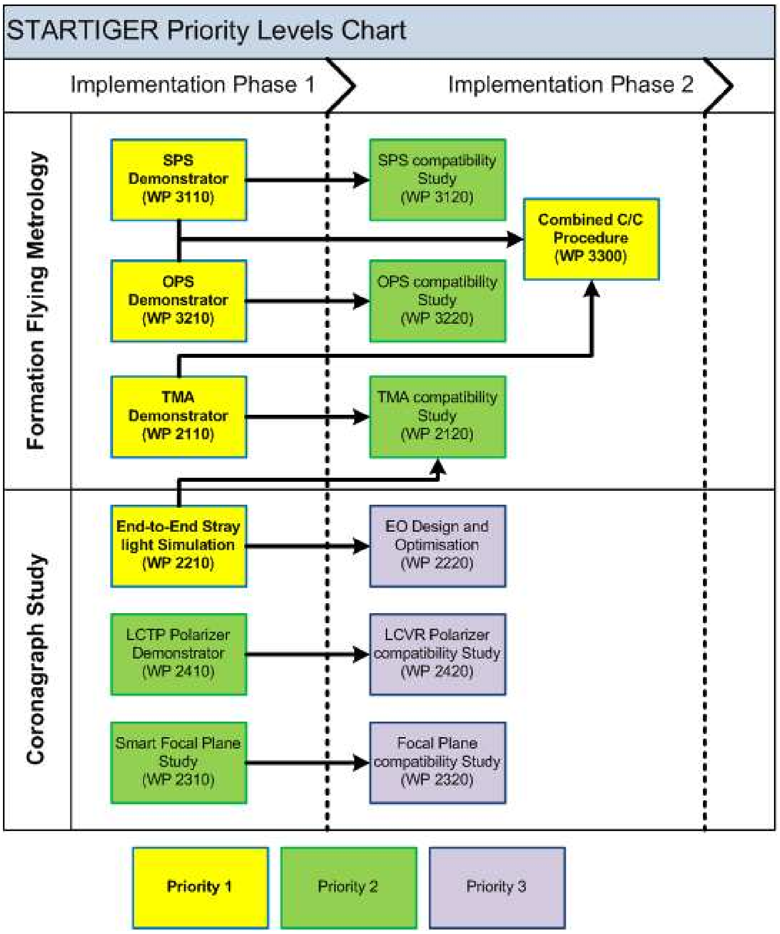

Figure 4.2 – Priority levels chart.

5 Description of activities

5.1 CORE-TEAM activities

The main activity of the CORE-TEAM is to develop a demonstrator validating the FF performances measured through the scientific payload (i.e., metrology of the FF with an independent unit further capable to calibrate the S/C FF systems).

The demonstrator will verify the accuracy of the measurement of both the absolute pointing and the relative pointing (i.e. alignment) of the formation flying with the following expected performances:

- Absolute pointing: ±20 milliarcsec off-pointing (i.e. lateral displacements of the shadow as low as ±15µm).
- Relative pointing (alignment): ±0.3 arcsec (i.e. ±1.5 µm in the lateral direction and ±10 cm in the longitudinal direction for 150 m baseline).

Note that these expected performances, derived from preliminary analysis, exceed those required by the future FF solar coronagraphs (e.g., for the PROBA-3 mission: ±3mm of lateral displacements and ±12arcsec relative pointing accuracy) thus offering substantial margins and confidence in the capability of our subsystems.

The FF demonstrator is composed of the units/sub-systems representative of those baselined for the PROBA-3 mission (TMA, SPS, OPS), and of units allowing the validation of these sub-systems (EOS, ASCS, MCU).

During the first implementation phase (i.e., from T1 to T1+4 months), the CORE-TEAM will mainly focus on the demonstration of individual performances of each sub-system.

Figure 5.1 shows the architecture of the FF demonstrator, and the functionalities and validation to be performed during the first implementation phase. Each individual sub-system will be designed, developed and validated at breadboard level. Figure 5.2 gives a schematic view of the FF demonstrator.

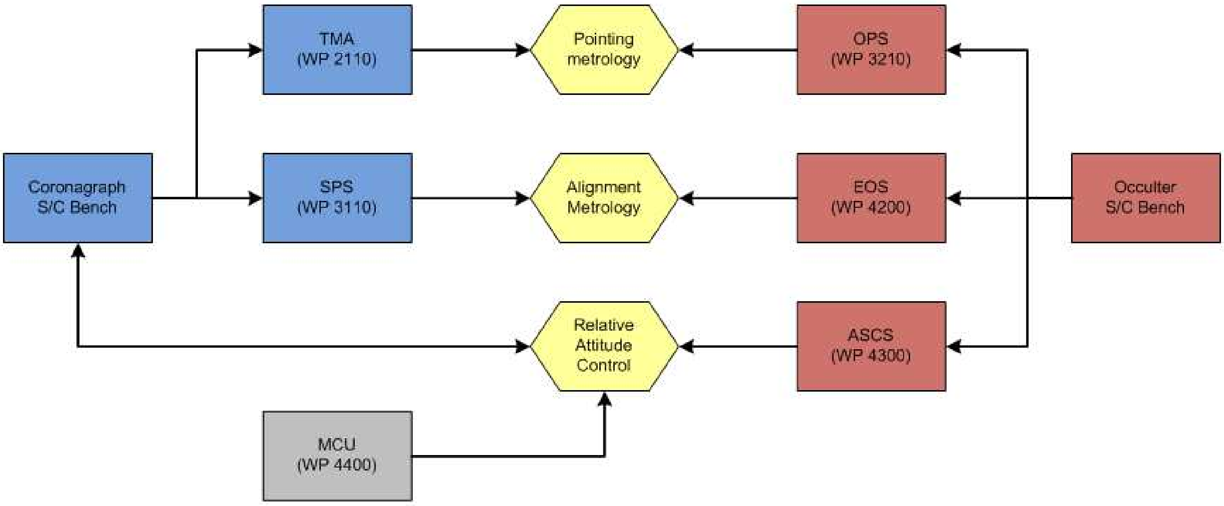

Figure 5.1 – Architecture of FF demonstrator: units and functionalities.

According to the high level schedule presented on Figure 5.3 (schedules at sub-system levels will be given in the following sections), the first month of the activity will be mostly dedicated to:

- Definition of the overall system architecture of the demonstrator;
- Consolidation of preliminary technical concepts and performances to be achieved;
- Detailed definition of sub-systems (from concepts to detailed design).

The following 2 months of the activity are dedicated to:

- Following up the manufacturing of sub-systems;
- Software development;
- Integration and Assembling.

Finally the last month of the first implementation phase is dedicated to the Individual tests of each sub-system, validating Absolute Pointing Metrology and Alignment Metrology.

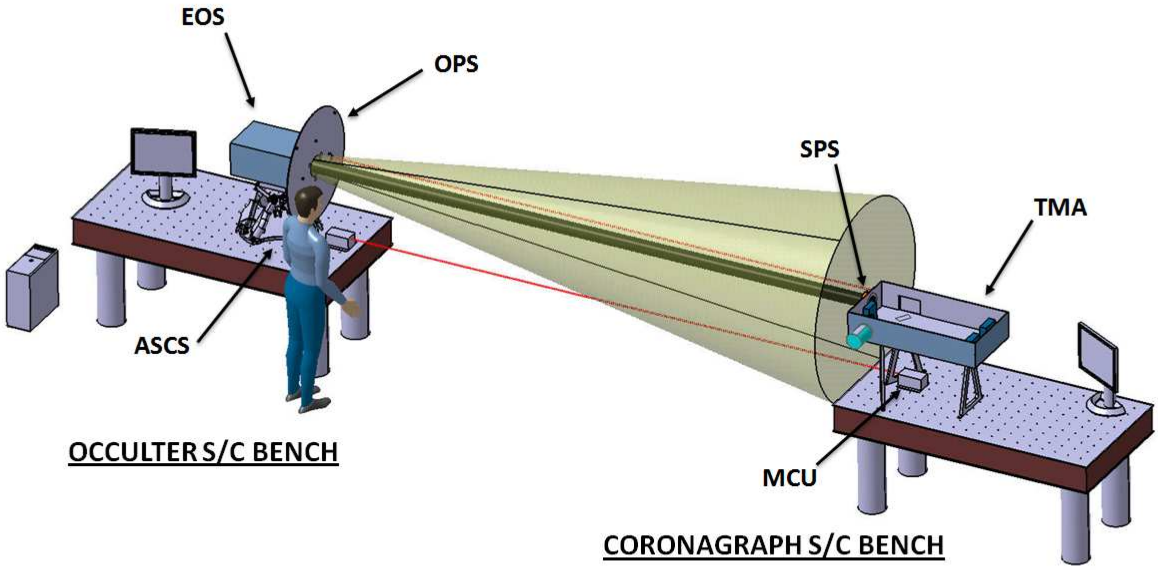

Figure 5.2 – Schematic view of the FF demonstrator (not to scale).

It is understood that these top-level steps are indicative of the progression of the activities, and that, in practice, they will be adapted to the flow of the tasks to be performed. For instance, Figure 5.3 shows that the ASCS calibration phase is advanced since ASCS is required for EOS calibration, itself advanced since required for the tests and validation of the SPS and OPS sub-systems. Details are given in the individual description of these demonstrators/functions in the following sections.

Following the individual validations of each sub-system during the first implementation phase, the final demonstrator will allow to implement and validate the in-flight procedure to align and point the FF. This constitutes the 2nd implementation phase planned for 2 months. During this 2nd phase, the combined use of the Absolute Pointing and Alignment measurements will demonstrate the required procedure, and the capability to achieve the FF configuration when starting from the two satellites in an arbitrary configuration.

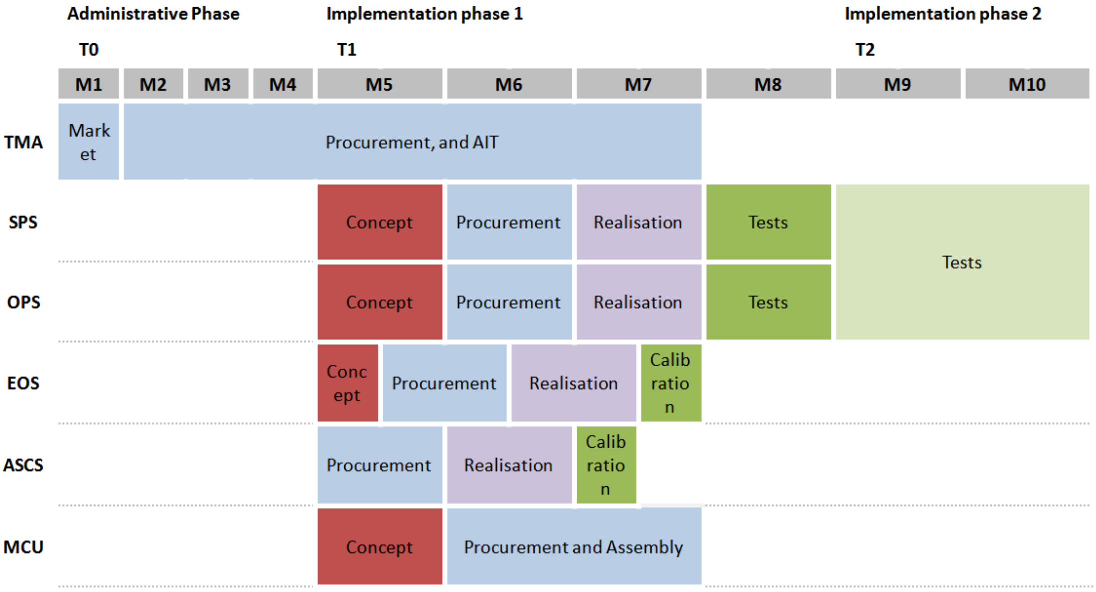

Figure 5.3 - High level schedule of activities to be performed by the CORE-TEAM.

THREE-MIRROR ANASTIGMAT (TMA) DEMONSTRATOR

Among various solutions which have been investigated, the TMA is the unique solution fully compliant with both the FF and the scientific requirements. The TMA Demonstrator is then an essential part of both:

- the coronagraph (high image quality and potentially large aperture),
- the FF validation since the TMA rigorously defines the optical axis to be used as a reference for aligning the two satellites.

Only a reflective solution is suitable to a coronagraph in FF since it provides a natural front baffle (in a reduced volume) blocking unwanted light (reflections and/or diffractions) arising from the penumbra region surrounding the entrance pupil. Basically, an equivalent classical refractive objective requires a longer instrument (by a factor 2). Note that the specific stray light simulations of a coronagraph in FF are addressed in the WP 2200 and are detailed in section 5.2.1.

The three-mirror solution has been preferred to the two-mirror solution in order to achieve high image quality over a large circular FOV (~1.5° diameter) thus allowing very low over-occultation by the internal occulter (i.e., making full use of the large distance offered by the FF to observe the corona as close as possible to the solar limb).

Furthermore, for the FF demonstration, the TMA demonstrator (WP 2110) is essential because the pointing is verified with respect to its optical axis which is perfectly defined in a reflective system. Note that this is not the case for a standard refractive objective which cumulates the drawbacks of low image quality and ill-defined optical axis.

The optical concept and alignment procedure and control of the TMA have already been developed by the LAM during the Phase A studies of PROBA-3 in 2007-2008. It is now well established and we are ready for its realization.

Description

The proposed solution is based on a three-mirror anastigmat (TMA) composed of 3 off-axis aspheric mirrors. An off-axis solution is required to avoid pupil obscuration so as to minimize stray light. As shown in Figure 5.4, the primary mirror is located 965 mm behind the entrance pupil.

The demonstrator will be composed of the three mirrors, their mounts (commercial or custom devices), the optical bench supporting all optical elements, the surrounding structure which supports the entrance pupil and the I/F with the camera (at the TMA focal plane).

The TMA, with its three mirrors, will be delivered mounted and aligned, and a standard verification of the optical quality will be performed at LAM.

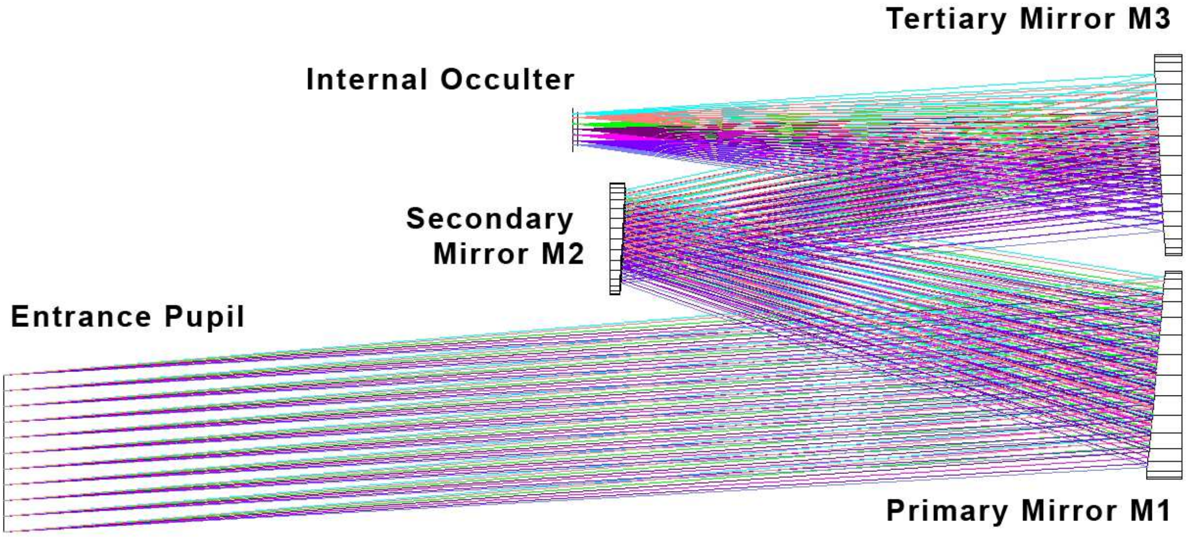

Figure 5.4 – Three-Mirror Anastigmat (TMA) optical layout.

Tests

The TMA demonstrator is involved in the demonstration of the alignment of instruments in FF but no specific optical tests are planned on the TMA demonstrator during the STARTIGER program. However, we have planned to re-use the TMA demonstrator to validate the use of such a concept in real conditions during a total solar eclipse in the summer 2010.

Schedule

The TMA demonstrator is fully subcontracted. Because of the long time required to polish mirrors with confidence, this activity is planned to start right at the time of the contractual Kick-Off (T0). Since the expected time to manufacture and polish the three mirrors is set (with confidence) to 5 months after discussions (and a first offer of realization) with one of the potential contractors, the STARTIGER first implementation phase is not planned to start earlier than 4 months after the Kick-Off (i.e. > T0 +4 months). Then, and following the high level schedule proposed (cf. Figure 5.3) the TMA Demonstrator mirrors will be properly polished at T1 + 2 months (T0 + 7 months), and delivered mounted and aligned, a month later, i.e. at T1 +3 months, ready for the Tests Phase of SPS and OPS, as expected for the successful completion of the first implementation phase of the STARTIGER study.

Risk

The polishing off-axis aspherical mirrors is always a concern although it is becoming more and more standard practice in the optical industry. Actions have been taken to minimize the associated risk by discussions with (and a firm offer from) one of the foreseen contractor. The maximum 5 months period for polishing, reported in the high schedule level of the First Implementation Phase, includes contingency. However, because the Public Market Rules in France require a competitive call, an advanced ITT may have to be done 4 months before T1, i.e., before the start of the first implementation phase of the STARTIGER activity.

In order to mitigate the risks associated to the manufacturing of the TMA and possible delays, a simple back-up solution consisting of an objective can be easily implemented, thus allowing starting the early activities of the test phase of SPS and OPS.

SHADOW POSITION SENSOR (SPS) DEMONSTRATOR

SPS is an important subsystem of coronagraphs in FF as it determines the absolute pointing of the instrument (i.e. the formation) by sensing the displacement of the penumbra formed behind the external occulter. The SPS also insures the safety of the coronagraph, by detecting direct solar illumination before it reaches its entrance pupil. It

The SPS accomplishes the centering of the entrance pupil of the instrument in the shadow cone of the occulting disc, by balancing the intensity received by light sensors located in the penumbra zone around the entrance pupil.

When the formation is nominal (i.e., the axis of the formation points to the Sun center), the penumbra light equally feeds all sensors. When the shadow moves, the SPS evaluates the displacement either by measuring the absolute signal of each sensor, or by comparing two diametrically opposite sensors. Then it supplies a signal nearly proportional to the displacement.

Description

The SPS concept is derived from a similar pointing sub-system implemented and successfully used on the SOHO/LASCO-C2 coronagraph. Furthermore, shadow sensors have regularly been used in space, especially for the detection of Earth's position. This past experience may prove useful and possibly applicable with appropriate modifications to the SPS development

The SPS demonstrator will allow determining the optimal specifications of such a concept in order to achieve the best performances. System analysis and numerical simulations will allow determining optimal specifications (e.g., location and number of sensors, solid angle seen by each sensor, etc.). Once the specifications are determined, the demonstrator will be designed and manufactured. Space qualified components will be used as far as possible to limit future developing efforts for the integration of this system in future space missions.

Schedule

The SPS demonstrator will be developed during the three first months of the implementation phase 1 (from T1 to T1 + 3 months). These three months are mostly dedicated to consolidation of the concept through numerical simulations, opto-mechanical and electronical concepts of the demonstrator, manufacturing follow-up, and C/C software development.

The SPS demonstrator will be integrated and tested during the last month of the first implementation phase.

The SPS demonstrator will also be used during the second phase (from T1 + 4 months to T1 + 6 months) for the validation of the Combined Control-Command Procedure for the Absolute Pointing and Alignment (WP 3300).

Tests

Tests will be performed in order to validate:

- The performances achieved in measuring FF absolute off-pointing (tilts);
- The performances achieved in measuring FF misalignments (lateral and longitudinal);
- The effects on performances of a differential response of sensors (e.g., error on the positioning of one or more sensors with respect to the entrance pupil center; different intrinsic response of sensors).

Risks

The only identified risk concerns possible delays which could occur during its development and particularly during the manufacturing which is subcontracted. This risk is mitigated by both discussions/agreement we already have with potential suppliers on the required time to manufacture each part of the SPS demonstrator; and the possible use of the LAM's machine shop in support of the manufacturing and assembly activities.

OCCULTER POSITION SENSOR (OPS) DEMONSTRATOR

The "Occulter Position Sensor" (OPS) is required to verify the relative pointing of the coronagraph axis with respect to the axis of the formation. In other words, it will be used to measure the position of the occulter in the FOV of the coronagraph, thus providing an independent verification of the stiffness of the formation. The OPS demonstrator will allow detecting the position, rotation, and alignment of the occulter (i.e., EOS breadboard) with respect to the coronagraph (i.e., TMA demonstrator).

Description

The OPS demonstrator is composed of light sources which are imaged by the TMA demonstrator onto a detector. By comparing the position of the photometric center of their images with reference pixels on the detector, we will be able to accurately compute the position of the occulting disk center compared to the optical axis of the coronagraph.

System analysis and numerical simulations will allow determining the optimal specifications (e.g., light sources specifications, optimal defocus onto the detector, etc.). Once these specifications are determined, the demonstrator will be designed and manufactured. Space qualified components will be used as far as possible, to limit future development efforts for the integration of such systems in future missions. Furthermore this sub-system will be designed and realized to cope with the various distances that will be used during tests, representative of the FF assembly. When integrated, each light source will be individually calibrated.

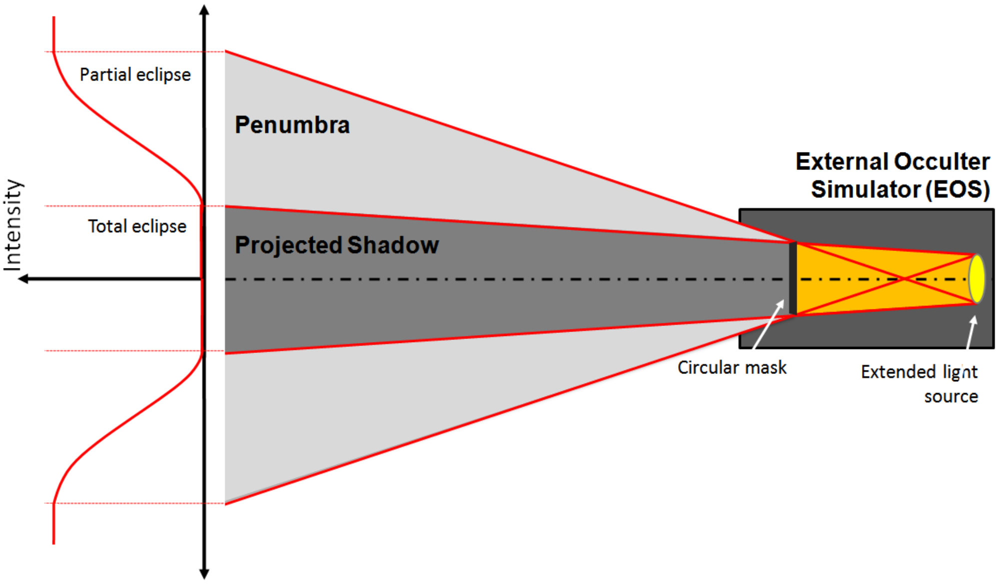

Figure 5.5 – Schematic concept of the EOS.

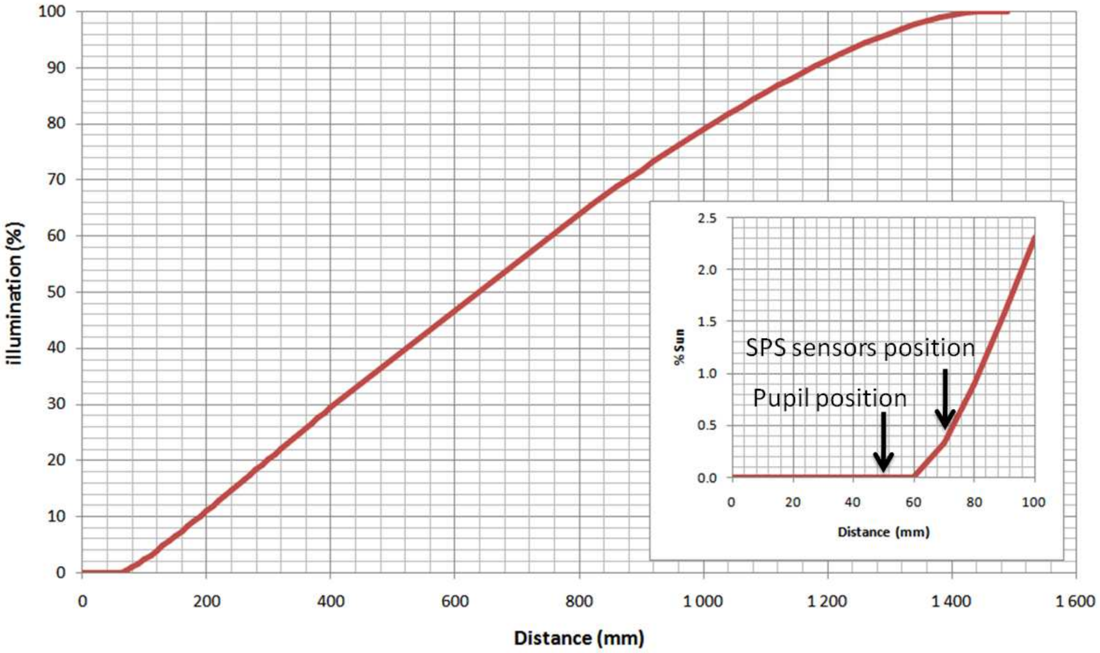

Figure 5.6 - Distribution of the illumination in the penumbra at the 150 m beyond the occulting disk. The distance is given in mm and is measured from the center of the entrance pupil of the coronagraph. Note that the SPS position is also indicated.

Schedule

The schedule is very similar to that proposed for the SPS demonstrator. The OPS demonstrator will be developed during the three first months of the implementation phase 1 (from T1 to T1 + 3 months). These three months are mostly dedicated to consolidation of the concept through numerical simulations, opto-mechanical and electronic studies of the demonstrator, manufacturing follow-up, and C/C software development.

The OPS demonstrator will be integrated and tested during the last month of the first implementation phase.

The OPS demonstrator will also be used during the second phase (from T1 + 4 months to T1 + 6 months) for the validation of the Combined Control-Command Procedure for the Absolute Pointing and Alignment (WP 3300).

Tests

The following tests will be performed in order to validate:

- The performances achieved in measuring FF relative positioning of one S/C bench with respect to the second (lateral, longitudinal, and tilts);
- The optimal specifications (light source defocus, S/N ratio, etc.) required to achieve the optimal performances;
- The effects on performances of a differential light source emission and/or positioning (e.g. sensitivity to dust; sensitivity to thermal deformation of the large structure supporting the OPS; etc.).

Risks

Risks are very similar to those mentioned for the SPS demonstrator and will be mitigated in the same manner, i.e. agreement with potential suppliers on the required time to manufacture each part of the demonstrator; and possible support of the LAM's machine shop.

EXTERNAL OCCULTER SIMULATOR (EOS) BREADBOARD

The EOS breadboard is a key element in the demonstrator since it produces the shadow and penumbra defining the absolute pointing of the instrument (i.e., the formation).

Description

The simulator is composed of an extended light source (simulating the "Sun") and a circular mask (equivalent to the EO) surrounded by a baffling structure (Figure 5.5). Their relative dimensions define the decreasing pattern of light intensity in the penumbra zone (Figure 5.6).

Numerical simulations will allow determining both the specifications of the EOS (dimensions of the light source, of the mask, distance, etc.) and extrapolating results to larger distances (e.g., up to 150 m or more). Indeed, the EOS will be so designed that it will be able to work at the various distances that will be used during tests, and which are representative of the FF assembly. Once the specifications are defined, the breadboard will be designed and manufactured. Calibrations will be performed prior to demonstrators' tests. In particular, the optical axis of the EOS will be verified with the MCU.

Schedule

Numerical simulations and concepts will be developed during the first half of the first month of the implementation phase 1. Procurement and realization will take 2 months (from T1 + 0.5 month to T1 + 2.5 months). EOS assembly, alignment and calibration will last 0.5 month.

Calibration

The gradient of the penumbra will be calibrated using a mobile light sensor moved perpendicularly to the optical axis and recording the intensity received. This calibration will be repeated several times (in particular during tests) to verify the stability of the penumbra pattern.

Risk

No risk has been identified. Furthermore, LAM has already experience in developing equivalent OGSE. Indeed LAM is already equipped with an Artificial Sun (designed, manufactured and aligned by LAM) which produces the image of the Sun as seen from 1 AU (Astronomical Unit, i.e. mean distance Earth-Sun).

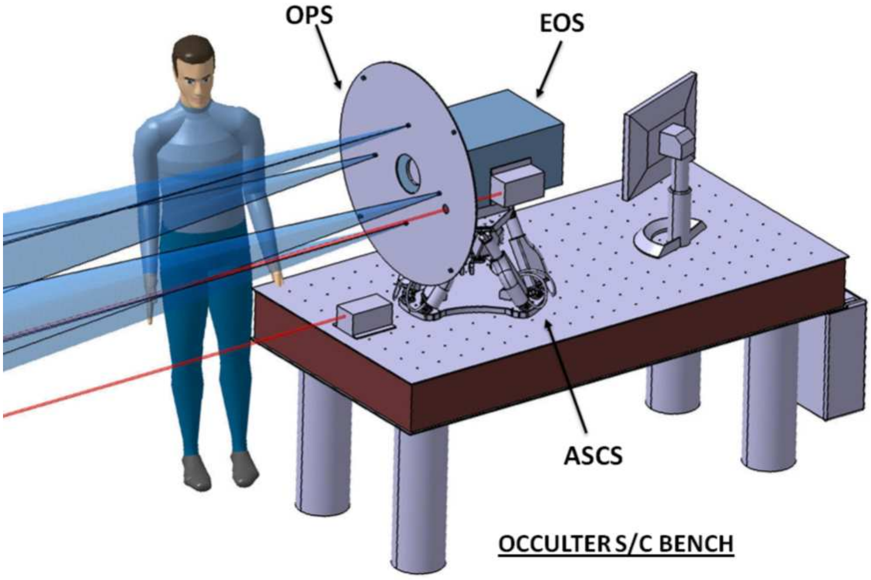

Figure 5.7 – Schematic view of the Occulter S/C bench (with OPS turned-on and EOS turned-off).

ATTITUDE S/C SIMULATOR (ASCS)

The Attitude S/C Simulator (ASCS) is required to simulate the attitude of one S/C with respect to the other. The proposed simulator is based on the hexapod technology which appears to be the most convenient and flexible solution to provide simultaneously all the degrees of freedom (DoFs) required for the demonstration.

Description

The hexapod device is composed of six identical high-stiffness electro-mechanical linear actuators which connect a mobile platform to a fixed base (Figure 5.8). The simultaneous and parallel control of the six actuators allows complex and accurate (absolute position and repeatability) motions in real time. The main advantages of such a solution can be summarized as follows:

- Six degrees of freedom available from a single controller;
- Robust and accurate kinematic solution avoiding cumulative errors (as in classical linear/rotation stages mounted in series);
- Configurable motion of the centroid (which allows in particular to decouple linear and rotation movements);
- Large dynamic range of displacements available.

Schedule

The ASCS is provided by LAM as part of its existing facilities (see section 7), and it does not require any development, except for an upgrade of its temperature control required to achieve the specifications (i.e. of a few µm).

Calibration

The implementation of the ASCS and its calibration will be carried out with the supplier of the hexapod (the Symétrie company), which has a long and successful experience in implementing such an equipment.

Risk

No risk has been identified; the activity only consists in upgrading our existing hexapod with additional standard equipment available from the Symétrie company.

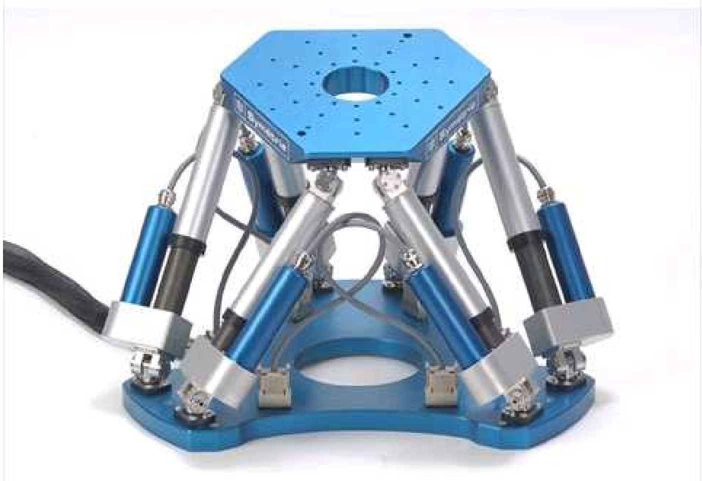

Figure 5.8 - The hexapod provided by LAM as a facility to the STARTIGER program. The hexapod is composed of six identical electro-mechanical actuators which connect the mobile platform to the fixed base.

Table 5.1 - ASCS performances. The displacement per axis corresponds to the individual displacement applied to each axis with the other axis at the mid-points of their own displacement range. Cumulated displacement corresponds to the maximum displacement achievable simultaneously on all axes.

Degree of Freedom	Displacement (per axis)	Cumulated displacements	Resolution	Accuracy
Linear disp. (Tx)	± 75 mm	± 10 mm	1 µm	2 µm
Linear disp. (Ty)	± 75 mm	± 10 mm	1 µm	2 µm
Linear disp. (Tz)	± 50 mm	± 10 mm	1 µm	2 µm
Angular disp. (Rx)	± 15 deg	± 10 deg	5 µrad	10 µrad
Angular disp. (Ry)	± 15 deg	± 10 deg	5 µrad	10 µrad
Angular disp. (Rz)	± 10 deg	± 5 deg	5 µrad	10 µrad

METROLOGY CONTROL UNIT (MCU)

The metrology control unit is dedicated to the external and independent metrology of the two optical benches.

Description

The MCU will be composed of:

- classical external optical metrology devices (such as MAT and theodolites) which will provide the external references of the two benches for initial alignment and calibration (direction, position offsets);
- specific tools (based on lasers and PSD – position sensitive device – optical sensors) which will provide a real-time control of the stability of the two benches.

Schedule

The most appropriate concept of MCU (both static and dynamic parts) will be defined during the first month of the implementation phase 1. Procurement, realization (if necessary), and calibration will take two months (from T1 + 1month to T1 + 3 months).

Calibration

Calibration will be achieved thanks to the external optical metrology devices as described above.

Risk

No risk has been identified since realization and measurements are based on classical optical metrology devices and techniques.

COMBINED COMMAND-CONTROL PROCEDURE

The validation of the Combined Control-Command Procedure for the Absolute Pointing and Alignment (WP 3300) will complete the demonstration of the Formation–Flying approach, ensuring its credibility. This is mostly a software task since acquisition and control cards (under LabView) are already available from the pointing and alignment validation tasks (WP 3110, WP 3210). In addition, the Sun sensor and the Coarse Lateral Sensor (which are baselined for the PROBA-3) could be introduced in the C/C procedure in order to simulate the overall calibration process, starting from an arbitrary pointing and alignment position of the FF.

The successful application on the demonstration benches of the complete procedure, starting from any arbitrary position, will validate the FF approach bringing to reality an exciting new technology enhancing satellite possibilities.

Description

This Combined Control-Command Procedure (C3P) provides an external and independent verification of the formation flying alignment/pointing. In the STARTIGER framework, we also intend to address the issue of the calibration of the metrology FF system (including subsystems from the payload and the satellite).

The C3P is a two-variable control-command-loop, in which the controller will have to interpret the signals from the SPS and the OPS to send orders to the hexapod (ASCS) in order to compensate for perturbation (misalignment and/or offset-pointing).

A quality/robustness analysis will be performed on the software developed with identification of the critical errors or functions.

These developing efforts will help and reduce the time for the developments required to program the software (FPGA) in ASPIICS/PROBA-3 and future space missions.

Schedule

The C3P ensuring the combined task of pointing and alignment will be developed and validated during the second phase of implementation, between T1+ 4 months and T1+ 6 months. It will use both the OPS and SPS demonstrators, and the ASCS for introducing offset-pointing and misalignments.

Writing of the complementary software necessary to integrate both the pointing information and the alignment information, with a link to the ASCS command to initiate the procedure process, is expected to take 1 month under LabView, this tool being largely used already for the GSE, and the measurements on the benches.

The second month will be dedicated to the multiple tests of the procedure (time of acquisition, level of residual error, cross-talk if any between pointing and alignment loops, etc.) and, during the last week, to a complete calibration test of the FF.

Tests

Tests will be performed in order to validate the control-loops of the Combined Control-Command Procedure for the Absolute Pointing and Alignment, and their performances:

- performances/errors as a function of the offset-pointing in the FOV;
- performances/errors as a function of the misalignments (lateral and longitudinal) between the S/C benches;
- cross-talk characterization in the control-loops.

A complete test of the calibration of the FF metrology system (including subsystems from the payload and the satellite) will close this activity.

Risks

There are no identified risks, as such, in the development of the procedure ensuring the combined task of pointing and alignment, as long as the initial validations of the Absolute Pointing measurement and Alignment measurement have been completed with the appropriate performances, and that precision and position potential are in within ASCS reach. A two-variable control-command-loop is a well-known development and much more sophisticated control-command operations have been carried by LAM and LATMOS in the past.

TRANSVERSAL OPTICAL, MECHANICAL, AND SOFTWARE ACTIVITIES OF THE CORE-TEAM

This section is not relevant to a unit or a specific function as illustrated in Figure 5.2, but to optical, mechanical, and software tasks required the proper realisation and validation of the FF demonstrator. The CORE-TEAM activities themselves are described in detail by each CORE-TEAM member in the Management Proposal (section 8.2).

Transverse optical activities encompass the development of all subsystems and will last at least one month. More specifically during the first month, the optical engineer (supported by the system engineer) will perform the optical architecture of the FF demonstrator and the associated OGSE. He/she will also develop the optical concepts and simulations of the OPS and the SPS.

Transverse mechanical activities will take place for each task of the CORE-TEAM. The mechanical design of the various demonstrators will be developed simultaneously during the first month by a team of 2 mechanical engineers under the responsibility of the mechanical architect. The phases of consultations and industrial production will require 2 months. The availability of the workshop of the LAM will be useful for modifications and adjustments if required.

Transverse software activities will concern the definition of software specifications, elaboration of algorithms, implementation of code, and performance verification. Those activities span the whole duration of each WP since the definition of software specifications corresponds to the concept period, the design to the procurement, and the implementation to the realization.

Specific AIT activities for each subsystem have been already described in the previous sections, mainly in terms of tests and calibration to be performed. There are obviously transverse AIT activities overlapping these specific AIT activities during the last month of the phase 1.

5.2 PARTNERS activities

5.2.1 Implementation phase 1

STRAY LIGHT STUDY

Straylight is a crucial concern in the optical design of classical externally-occulted coronagraphs, and it requires utmost attention to achieve the required performances. Coronagraphs suffer from light diffracted by the edges of the occulting disc which is the main source of stray light. Usually the instrumental stray light (produced inside the coronagraph) is minimized by using classical techniques such as internal occultation (at the expense of the loss of the very inner FOV), apertures and stops. Increasing the distance between the coronagraph entrance pupil and the occulting disc allows improving drastically stray light instrumental level. FF is then the most interesting technique to improve image contrast (i.e. reduce stray light) and observational access to the very inner FOV (avoiding over-occultation and vignetting effect).

Description

In the case of coronagraphs in FF, in addition to the classical optimization of both the instrument (TMA) and the occulting disk (WP2220), specific attention should be paid to the spacecraft environment. Of particular concern is the rear face of the occulting disc facing the coronagraph. While specified as black as possible in the scientific spectral bands, it hosts several GNC systems which may be illuminated by either the Earth or the Moon even they are outside the specified UFOV (Unobstructed Field of View in this case means region were Moon and Earth are excluded during operational mode). To cope with these constraints, particular attention has to be given to the micro-roughness of the manufactured mirror, and to the design of appropriate baffling system. To be confident with the selected design, modeling and simulations are mandatory. The main objective of the work is to develop a stray light model allowing to:

- Simulate the TMA up to its internal occulter (see Figure 5.4), including preliminary design of the baffle layout;
- Simulate the diffraction due to the external occulting disk located at various distances from the coronagraph (assumed to be a single disk i.e. circular and thin);
- Define the requirements to be imposed on surface properties of the occulter (specular & diffuse reflection); i.e. make a parametric study of the reflective/diffuse surfaces at the rear side of the EO to define the limits of what can be accepted concerning the visible

face of the occulter. Accepted BRDF of the coating specification and maximum luminance x maximum area will be specified at the level of the rear plane of the external occulter.

Methodology

The model will be developed with ASAP or FRED. Stray light analysis with ASAP is strongly limited by the computation time. ASAP model uses scattered rays: for each incident ray (“parent”) on a surface a determined number of “kids” rays is created with intensity linked to the surface BRDF, the incident angle of the « parent » ray and the scattering angle of the « kid » rays. In order to limit the number of needed scattered rays, the surface is considered to scatter the « kids » rays in adequate directions. The choices of these adequate directions determine the quality of the results. The rejection is computed by the ratio of the collected flux in the focal plane to the incident flux at the baffle entrance. This means that for a 10^{-12} rejection rates, at least 10^{15} rays need to be generated. For instance, this required 24h computer time for the COROT baffle analysis.

Analysis

A geometrical analysis limited to first order will be performed to verify whether there is any critical surface and whether there is any vignetting in the FOV (surface directly illuminated and seen by the mirror). Stray light coming from the spacecraft will not be considered. Baffle tolerancing and thermo mechanical effect on the stray light rejection are not part of the proposed study. As indicated above, BRDF measurement of the black coatings will provide a higher degree of confidence in the ray-trace analyses that are used to optimize and predict the stray light rejection performance for the earthshine.

Schedule

This activity will take place at CSL during 2 months (from T1 + 1 month to T1 + 3 months).

LIQUID CRYSTAL TUNABLE-FILTER POLARIZER (LCTP) DEMONSTRATOR

The Liquid Crystal Tunable-filter Polarizer (LCTP) is a key element in our quest for enhanced science capabilities of future space coronagraphs. The successful demonstration of such a device within the STARTIGER program will pave the way for its possible inclusion in the PROBA-3 coronagraph (and certainly in any future instruments relying on polarization) opening magnetic field diagnostics. Indeed, polarimetric measurements of coronal emission lines provide a mean for tracing the direction of the coronal magnetic field, a key physical parameter

Principle

Liquid crystal tunable Filter (LCTF) allows the spectral range of the filter to be shifted throughout the visible-light bandwidth region, without moving parts. The optical filter design relies on the concept described by Bernard Lyot in 1933. While the so-called “Lyot” design provides a static bandpass, the addition of liquid crystal variable retarders provides spectral tuning capability. In essence, a series of similar optical elements consisting of linear polarizer and fixed waveplates, and LCs are bonded together. Each element transmits light with transparency that varies sinusoidally as a function of wavelength. The transmitted light adds constructively in the desired bandwidth region, and destructively outside the passband, with a transmission of 0.01% or less.

Description

The Liquid Crystal Tunable-filter Polarimeter (LCTP) consists in a combination of a LC Tunable Filter (LCTF) and a LC Polarization Rotator (LCPR).

The heart of the tunable filter consists of multiple liquid crystal variable retarders, invariant retarders, and polarizers all protected in a temperature-controlled housing. Varying the voltages applied to the liquid crystals shifts the pass band without any mechanical motion or vibration of the optics. Thus the filter can be tuned practically an infinite number of times since there is no wear and tear.

The LCPR is composed of a LC Variable Retarder (LCVR) combined with a fixed quarter-wave retarder and a linear polarizer arranged in “Senarmont” mount.

In the Polarization Rotator, the LCs birefringence is electro-optically adjustable. The resulting polarization modulation allows the analysis of the input linear polarization. The output from the LCPR’s polarizer goes through the LCTF for in-band and off-band wavelength selection.

The LC tunable filter passes only a narrow bandwidth of light while blocking all others within the spectral range. The pass band can be electro-optically shifted to a new wavelength in tens of milliseconds. This combination of pass band and speed is equivalent to thousands of dichroic or interference filters on hundreds of filter wheels. These advantages permit the user to acquire images in-band and off-band in a very short time.

The opto-mechanical package of these two devices is quite compact. The resulting LC Tunable-filter Polarimeter will determine the input linear polarization by tuning the LCVR into three different retardances. This measurement will be repeated both in- and off-band by tuning the LCTF. In this way, the LCTP yields the image polarization in-band (i.e., coronal emission-line) and off-band (i.e., K-corona polarized-brightness).

The proposed demonstrator will include both the LCPR and the LCTF mounted together in a single integrated device.

Tests

In order to test the expected LCTP capabilities, the demonstrator will be characterized at the Coronagraphic Lab of INAF-OATo. This facility includes a Muller-matrix Spectro-Polarimeter (MSP) used for complete polarimetric analyses:

- Muller matrix measurement of the LCTP polarimetric assembly.
- Characterization of LCPR voltage-rotation relationship, i.e., calibration of the polarization modulation versus applied voltage.
- Characterization of LCTP polarimetric response at different visible-light wavelengths (450-680 nm) and temperature.

The LCTP demonstrator will be also used for ground-based tests during the total solar eclipse of 11 July 2010.

Schedule

The LCTP will be developed during the first implementation phase:

- LCTP Specification definition: 0.5 month
- Procurement: 2.5 months
- Polarimetric characterization and validation: 1 month

Risk

Individually, the LCPR and LCTF devices are commercially available. The combination of the two devices into a single opto-mechanical package, the LCTP, will represent a custom-made procurement. Preliminary discussions with the manufacturer have indicated no particular risks associated to this operation.

SMART FOCAL PLANE STUDY

Typical large-format, state of the art CCD detectors (with pixel size ~ 15 microns) can achieve an electronic signal dynamic range of ~ 10,000:1 whereas current CMOS Active Pixel Sensors achieve ≤ 3000:1. In the case of the CCD this is limited by the 15 micron pixel size and resulting full-well capacity, whereas the limitation in CMOS sensors is more concerned with pixel capacitance and the resulting and fundamental compromise between well capacity and readout noise. In the case of the 15 micron pixel CCD, the well capacity is ~250,000 electrons such that the pixel shot-noise limited signal dynamic range is ~500. For CMOS sensors, the equivalent well capacity is ≤ 100,000 electrons, implying a shot-noise limited dynamic range ~300. For CMOS sensors, electronic dynamic range can be increased by allowing a degree of signal dependent non-linearity.

An alternative and preferable solution worthy of study would be the possibility of a design that incorporates “smart” exposure and readout control, individually tuned for each pixel. The input to the study will be a baseline definition of the detector requirements, for example:

- Image format;
- Pixel size;
- Exposure time and thus also frame readout rate;
- Anticipated minimum and maximum signals.

Taking the baseline definition, the study will consider the design and model the performance of a basic 3-transistors CMOS APS pixel. Optimisation of pixel design is critical to maximising sensitivity and dynamic range. Pixel design, and in particular the photodiode design becomes even more critical for those sensors that are to be thinned and back-illuminated to maximise quantum efficiency.

Taking the basic sensor design, the study will then consider the feasibility for extending the signal dynamic range by incorporating smart exposure and readout control, individually tuned for each pixel. A key aspect is the modification of the sensor's overall architectural design to enable random access to individual pixels and individual exposure control - we are aware of some work in this field at the Jet Propulsion Laboratory (US).

The study will proceed to modelling of the anticipated sensor and system performance against the original detector design requirements. Consideration will be given to the work needed in the next phase if the conclusion is to employ a new CMOS APS sensor rather than a more conventional CCD system. In particular the study will:

- Recommend appropriate CMOS processes for detailed design and fabrication.
- Requirements a programme for sensor verification and qualification.
- Discuss requirements and issues concerned with radiation damage and radiation hardening.

5.2.2 Implementation phase 2

Through the CORE-TEAM activities, we are expecting to bring most of critical sub-systems (i.e., TMA, SPS, and OPS) from conceptual level (TRL 1-2) to breadboard demonstrators (i.e. TRL 4). In addition, these sub-systems will be studied to determine their compatibility with the PROBA-3 mission.

COMPATIBILITY OF THE TMA FOR THE PROBA-3 IMPLEMENTATION

The TMA is of prime importance for both the FF metrology and the scientific achievement of the coronagraph. The implementation of the TMA in the framework of the PROBA-3 mission (i.e., the TMA-PROBA model) must be studied in terms of feasibility and compatibility.

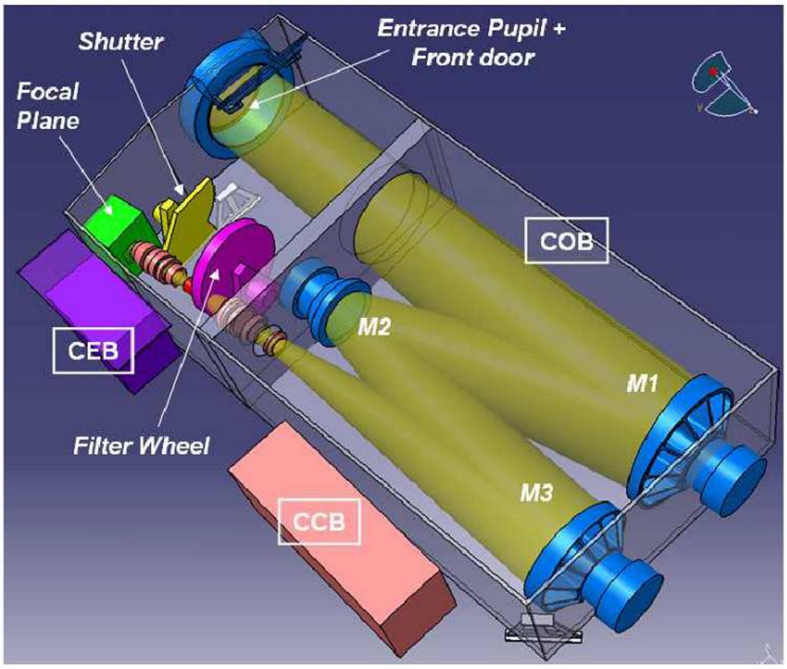

Figure 5.9 - Mechanical design of the FF coronagraph developed during the phase A of the PROBA-3 mission. COB: coronagraph optical box; CCB: coronagraph Control Box; CEB: coronagraph Electronics Box.

The detailed activities are listed below:

- Determination of the complete optical tolerancing (including manufacturing tolerances, alignment parameters ranges, launch effects, operational thermo-elastic effects, …);
- Definition of the opto-mechanical design of the optical mounts;
- Definition of the opto-mechanical design of the optical bench;
- Verification of the overall TMA mechanical concept;
- Thermo-elastic evaluation (FEM Analysis if needed) and thermal control definition;
- Comparison of FEM model and TMA demonstrator.

This activity will last 3 months (from T1 + 3 months to T1 + 6 months), and will be performed at CSL, except the FEM (Finite Element Model) calculations which will be performed at LAM. This activity is part of the second implementation phase, although optical tolerancing computations will be performed during the last month of the first implementation phase.

COMPATIBILITY OF THE SPS FOR THE PROBA-3 IMPLEMENTATION

The SPS compatibility study (WP 3120) will determine the compatibility of the SPS concept (validated through its demonstrator, i.e., WP 3110) with the coronagraph proposed for PROBA-3. The implementation approach assumes off-the-shelf, inexpensive, reliable components. This should help to limit the costs, and shorten the developing time needed for such a critical system. The WP 3120 will produce three different documents, all connected with the demonstration system produced by WP3110:

- A technical specification document of all the technologies and constrains that apply to the proposed concept.
- In the event that new technologies are required for the implementation of the SPS, a detailed description of the qualifications required for those technologies to be included in PROBA-3. As mentioned above, every effort will be made to avoid using unproven technologies.
- A product definition document that will contain the following sections:
    - Architectural description of the design. This will include the mechanics, electronics, optical, thermal, electrical, power and software descriptions;
    - Detailed specifications of each component;
    - Product description. This will include detailed descriptions of all components. Physical properties of the components, such as mass, CoG, dimensions, referential, tolerancing, internal interfaces will also be reported.
    - Functioning modes. The valid modes of the design will be defined;
    - External interfaces definition. This section will describe all aspects of the external interfaces, such as mechanical, thermal, electrical, and electronics.

COMPATIBILITY OF THE OPS FOR THE PROBA-3 IMPLEMENTATION

Similarly to the SPS (WP 3120), the OPS compatibility study (WP 3220) will be based on the same approach and will produce the same documents, all connected with the demonstration system.

COMPATIBILITY OF THE FOCAL PLANE FOR THE PROBA-3 IMPLEMENTATION

The focal plane compatibility study (WP 2320) will consider the design implementation for the detector focal plane assembly for the coronagraph proposed for PROBA-3. A key decision is whether to implement the design using a conventional science-grade CCD system or the CMOS APS detector arising from WP 2310.

The aim of this WP will be to study the implementation of a focal plane assembly for the coronagraph. This relies on taking the instrument-level system requirements and the detector-level requirements:

- Image format.
- Pixel size.

- Exposure time and hence frame readout rate.
- Anticipated minimum and maximum signals.

Selection of either a conventional CCD imaging system or the proposed CMOS APS (from WP2320) will be considered. Of relevance are the following other consideration that contribute to the overall focal plane detector system:

- The ancillary electronics needed to operate the focal plane detector.
- The required proximity of the readout electronics which may influence the maximum detector readout rate also bare on thermal requirements for cooling of the focal plane.

The study will:

- Generate a baseline concept for the detector focal plane design.
- Define readout electronics requirements and propose system concept.
- Define electrical interfaces.
- Define thermal interface requirements.

COMPATIBILITY OF THE LCTP POLARIZER FOR THE PROBA-3 IMPLEMENTATION

The Liquid Crystal Tunable-filter Polarizer is highly attractive to enhance the science return of the PROBA-3 coronagraph. This all-electro-optical package will have the capability of i) analyzing the linear polarization of coronal emission lines and of ii) tuning the wavelength bandpass on and off the emission lines of interest. This LC Tunable-filter Polarimeter (LCTP) has no moving parts and this makes particularly appealing when mass and power resources are limited, and when a high number of reliable operation cycles are required.

This compatibility study will focus on the following aspects:

- Definition of the instrumental parameters of the LCTP that best match the science requirements within the resources available to the coronagraph (mass, power, telemetry) and the imposed environmental constraints (temperature, radiation);
- Optical compatibility with the currently proposed optical design of the coronagraph;
- Mechanical compatibility with the currently proposed optical design of the coronagraph;
- Electrical requirements for the LCTP and their impact on the on-board electronics;
- Space qualification of the LCTP.

This compatibility study will last one month and will result in the production of a report covering the above aspects.

EXTERNAL OCCULTER DESIGN AND OPTIMIZATION FOR PROBA-3 IMPLEMENTATION

In classically externally-occulted coronagraphs, the main source of stray light results from solar light diffracted by the edge of the occulting disc. Over the last thirty years, the improvements have been targeted to inventing sophisticated devices – triple disc, serrated disc, multidisk - to reduce the level of the diffraction fringe. Although formation flying will considerably improve the situation by the 1/D dilution factor (where D is the distance between the two satellites), this will be partly offset by the scientific requirement to look closer to the solar limb, thus reducing the large over-occultation inherent to classical coronagraphs. The design of the external occulter (EO) for the PROBA-3 mission must therefore be carefully investigated. In addition, with FF, we move from “small” EO with diameters of a few centimeters to “large” EO with diameters exceeding 1 meter. Mechanical (robustness) and ground operation (handling, integration on the S/C and in the launcher) constraints become strong drivers in the design of the EO. In that respect, occulters relying on sharp edges such as multiple and serrated disks may not be appropriate. Truncated cones and barrel shaped occulters appear as possible alternatives. The proposed study will allow ascertaining the best solution.

The detailed activities are listed below:

- Numerical calculation of the diffraction by various discs. This requires that (a) the existing simulation software be extended from a point source (presently available) to an extended source (i.e., the solar disc), and (b) manufacturing imperfections be quantified, parameterized and introduced in the software. Task (a) will be achieved by defining a matrix of source points on the solar disk, as described in Landini et al., Appl. Opt. 45 (26), p. 6656, 2006. Task (b) will rely on a statistical approach, but measurements may be necessary in order to obtain realistic values of the parameters;
- Definition of a mechanical design fulfilling all constraints;
- Determination of the complete tolerancing (including manufacturing tolerances, alignment parameters ranges, launch effects, operational thermo-elastic effects, …);
- Thermo-elastic evaluation (FEM Analysis if needed).

This activity will last 2 months (from T1 + 4 months to T1 + 6 months), and will be performed at INAF-OATo (Italy). This activity is part of the second implementation phase.

This WP 2220 activity will produce a document containing the results of the optimizations performed; the technical specifications of the preferred solution; and short description of the final product (including opto-mechanical architecture and main properties).

6 Key Technological Areas

Table 6.1 indicates the TRL level of each of the sub-systems involved in the study at beginning and the level it will reach after Phase 1, and the level it could reach after implementation of the recommendations of the 2nd Phase compatibility studies.

In practice, the sub-systems/demonstrators will reach TRL 4 at the end of the First Implementation Phase (T1 + 4 months), and the Compatibility Studies will pave the way to reach TRL 6 (in the context of the PROBA-3 project).

Table 6.1 – TRL levels to be achieved.

Sub-system	**Current**	**End of phase 1**	**End of phase 2**
TMA	2*	4	⏩ 6
SPS	1	4	⏩ 6
OPS	1	4	⏩ 6
LCTP	2	4	⏩ 6

* Concept and/or equivalent device already used in previous space instrument.

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7 Facilities involved

The new building of Laboratoire d'Astrophysique de Marseille (LAM, France) will be the co-location place where the CORE-TEAM activities will take place (Figure 7.1).

The building consists of office space and a technical area composed of optical experimentation rooms (including two long optical "tunnels"), a metrology laboratory, a mechanical workshop and a clean room zone with sixteen clean rooms classified ISO 5, ISO 7, and ISO 8, including a 400 m² integration hall (ISO 8, i.e., class 100.000).

A large room within the office space will be provided and specifically equipped for the CORE-TEAM activities: computers, telecon center, videoprojection, etc… Optical (Zemax EE) and mechanical (CATIA) softwares will be made available to the CORE-TEAM members.

The two benches will be installed first in one of the optical tunnel in order to achieve the first validation of the FF demonstrators at reasonable distance (i.e., 20 m). The distance will be doubled by using the large flat mirror usually used for interferometric verifications during polishing processes. Note that this optical tunnel can be connected to the neighboring polishing room thus increasing the available distance to 30 m (or 60 m with the folding mirror). During the last month of the second implementation phase, we plan to use the integration hall to increase the distance up to 80m.

As already discussed section 5.1 (ASCS simulator), we plan to use the hexapod facility available at LAM. The hexapod is a general purpose device developed by a French company named Symétrie. This facility will be upgraded as described in that section.

The LAM metrology laboratory is equipped with a 500 x 500 x 500 mm tri-dimensional measuring machine and a FARO device which is a portable measuring arm that can make measuring of complex objects. The working volume is 1.8 meter. Classical optical metrology equipments will also be used for alignment purpose (e.g. theodolite, Micro-Alignment Telescope, …).

The LAM workshop is a 400 meter square facility fully equipped with small and large standard machine tools, and numerically controlled milling machine and lathe. The workshop staff is also available for consultation and advice on all aspects of design and fabrication.

The STARTIGER documentation at LAM will rely on the "Baghera" system, a tool developed by CNES for the documentation and configuration control of project documentation. All the STARTIGER documents will be made available to the whole team members through a Baghera WEB interface. Baghera allows access to authorized persons, through its web interface, to consult the document reference.

At the Osservatorio Astronomico Torino (INAF-OATo), the Muller-matrix Spectro-Polarimeter (MSP) of the Coronagraphic laboratory will be used to perform a full polarimetric characterization of the LCTP at different visible-light wavelength (450-680 nm).

We request that equipments, both existing and upgraded in the framework of the STARTIGER program and equipments procured within this program remain available at LAM for future PROBA-3 activities until launch.

Figure 7.1 – The new building of Laboratoire d’Astrophysique de Marseille (LAM, France).