INSTRUMENTAL APPROACHES TO ACHIEVE THE MEASUREMENTS REQUIRED FOR EXPLORING THE ENERGETICS, DYNAMICS, AND FINE-SCALE STRUCTURE OF THE SUN'S MAGNETIZED ATMOSPHERE

U. Schühle
Max-Planck-Institute for Solar System Research, Max-Planck-Str. 2, 37191 Katlenburg-Lindau (Germany)
Email: schuehle@mps.mpg.de,

ABSTRACT

An overview is given about the technical implementation of the remote sensing instrumentation of the Solar Orbiter mission. We will discuss the "science implementation" related to the specific scientific goal "Explore the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere". The technical approaches to implement the observational scenarios outlined in the Science Requirements Document (SRD) are reviewed. Some technical design options proposed for the remote sensing instruments will be shown in detail and some open technical issues are highlighted in regard to answering the question "How do we achieve this goal?".

1. INTRODUCTION

To explore at all latitudes the fine-scale structure and dynamics of the Sun's magnetized atmosphere, one of the four main goals of Solar Orbiter, requires combined observations from many of the instruments aboard the spacecraft. This concerns mainly the set of remote sensing instruments of the Solar Orbiter platform and, thus, the alternative title of this contribution may be "Instrumental Approaches to the Remote Sensing Instruments of Solar Orbiter".
In the case of Solar Orbiter, novel technical solutions (compared to previous missions) are required to cope with, e. g., the higher heat input, higher radiation dose, lower telemetry rate, and more stringent cleanliness requirements. These lead to restrictions and possible compromises in the science performance which we shall exhibit.

In this paper we will first review the history of the payload definition that led to the present status. Then, the present design status of instruments will be given and some of the technical solutions found will be highlighted. However, this will be done only briefly here, as many contributions to these proceedings will cover in detail the descriptions of individual instruments in their present design status. Some technical issues that are still to be solved will be considered finally.

2. INSTRUMENT SPECIFICATIONS

The remote sensing instrumentation of Solar Orbiter consists of a suite of instruments that must cooperate in order to study the plasma conditions and dynamics, and to provide boundary conditions for understanding the *in-situ* measurements. Therefore, to design this suite, it has to be kept in mind that each individual instrument contributes to the overall goal of diagnosing the entire range of plasma parameters of the solar atmosphere.

2.1 Historical background

A Remote Sensing payload Working Group has been set up by ESA with the main goal of studying feasibility of the payload instrumentation and defining open technical issues which need further study. Finally, after results from industrial studies of possible spacecraft configurations have been received, a strawman payload instrumentation could be defined. An overview of the Report of the Remote Sensing Payload Working Group is given by R. Harrison [1].
The strawman payload instrumental package has been specified in the Payload Definition Document (PDD), based on the requirements given in the Science Requirements Document (SRD). Specifically, a vector magnetograph (VIM), an EUV imager (EUI), a spectrograph (EUS), a coronagraph (COR), and an Xray imager (STIX) are required to achieve the mission goals and, in particular, to investigate the links between the solar surface and the corona. These instruments baselined by the SRD are finally specified in the PDD (Version 5).
The Payload Definition Document is a compilation of the Solar Orbiter reference payload requirements and of their design. This design has gone through several phases of review by industrial study and instrument consortia. As a result, the payload architecture of the remote sensing units was constrained to 1-meter class instruments with resolution limits of 1 arcsec and a general design rule obeying a "keep it simple" strategy.

2.2 Specifications (PDDv5) of the remote sensing instruments

The detailed design of the reference payload is described in the PDD (v5) and the requirements specifications are summarized in a table in that document. Here I will only summarize the main characteristics and requirements specifically related to the science performance.

VIM: The Visible Light Imager and Magnetograph will measure the magnetic and velocity fields in the photosphere. It consists of a Full Disk Telescope (FDT) and a High Resolution Telescope (HRT) who will share a common filtergraph which will be selected sequentially to provide maps of the vector magnetic field and the velocity field.
The main technical characteristics can be summarized as:

- FOV > 15‘ (HRT), > 150‘ (FDT)
- pixel size 0.5“ (HRT)
- cadence < 1 minute
- magnetograph range: 10 G to 3.5 kG
- velocity range: > 47 km/s
- imaging uniformity: 0.5% (flat-field)

EUS: The Extreme Ultraviolet Spectrometer will be employed to acquire emission line profiles for plasma diagnostics of the solar atmosphere, providing density, temperature, element abundances, flow speeds, structure and evolution information of plasma between chromospheric and coronal temperatures. The reference instrument is a normal-incidence, off-axis Gregorian system with a parabolic primary mirror and a stigmatic grating spectrometer.
The main technical characteristics are:

- spectral coverage: appropriate line selection (17 - 22 nm, 58 - 63 nm, > 91.2 nm)[1]
- FOV = 34‘
- spectral resolution $\Delta\lambda = 2$ pm
- pixel size 1“
- cadence < 1 minute

EUI: The Extreme Ultraviolet Imager is a suite of up to three high-resolution imaging telescopes (HRI), operating in different spectral bands comprising strong emission lines, and one Full Sun Imager (FSI). Together, these instruments will provide context images at different plasma temperatures of features on the solar disk as well as structural images of the solar corona.

Their instrumental characteristics are:

- spectral coverage: 2-3 coronal and cool lines (HRI), 1 coronal line(FSI)
- FOV > 3‘ (HRI), > 5.5° (FSI)
- pixel size 0.5“ (HRI), > 9“ (FSI)
- cadence < 1 minute

COR: The coronagraph of Solar Orbiter is primarily designed to measure the polarized brightness of the visible-light (K-) corona from which the large scale structure and the electron density of the corona can be derived. An externally acculted off-axis Gregorian telescope design has been assumed for this instrument, with a visible-light channel and an optional UV channel at H I Lyman-α, plus another optional EUV channel at the He II 30.4 nm line.
The main instrumental characteristics are:

- FOV 1.2 to 3.5 R at perihelion.
- Resolution: 16“ at 1.2R, 40“ at 3.5R
- Polarization sensitivity < 1 %
- cadence < 5 minutes
- UV imaging optional at 121.6 nm

STIX: The Spectrometer/Telescope for imaging X-rays will measure the X-ray continuum (Bremsstrahlung of energetic electrons) of impulsive events, providing the location, time, structure, and energy of the X-ray emission sources on the Sun, which may be detected subsequently by *in-situ* instruments.
The instrument-specific characteristics are:

- energy range 3 to 150 keV
- spectral resolution 2 to 4 keV (FWHM)
- FOV > 24‘
- pixel size 2.5“ (angular resolution)
- cadence < 8 Hz basic cadence + on-board selection

All instruments (except STIX, using a64x64 array) are designed to use focal plane detectors with 2kx2k pixel array format. A CMOS-APS solution is preferred, as better radiation hardness is expected of these than for CCD sensors.

2.3 Main technical issues to be solved

Several technical challenges have been identified by the Payload Working Group, resulting from the complex orbit of the mission and the resulting limitation of resources. They have to be tackled during the design phase of the spacecraft and the payload:

- The management of the thermal heat input, varying through the orbit: it may require a variable heat transfer to space radiators; the sizes of instrument apertures are limited, simply because the area for space radiators, needed to dissipate the heat, is limited on the sides of the spacecraft; the extreme heat flux entering through the apertures must be

[1] A different set of spectral bands has been selected by the EUS science consortium.

partly absorbed by baffles to be designed, and the heat shield and instrumental doors are to be designed.

- The development of 2k x 2k radiation-hard detectors has to be pursued.
- Space qualifications of optical elements, e. g., mirror and filter coatings, exposed to space radiation environment, have to be made.
- The cleanliness requirements may be very difficult to fulfill, given the variable thermal conditions.
- The data rate limitation requires novel techniques of on-board data reductions and compression schemes.

3. Instrumental design solutions

For each of the instruments, consortia have formed in which the different design options have been studied and discussed. Some resulting solutions that seem to be feasible have been accepted as their baseline solution, while in most cases backup solutions are also available. Most of the solutions will be described in much detail in the respective presentations of this conference. Below is just a brief overview with some examples, and the reader is referred to the individual contributions in this book.

3.1.1 Heat management

It was agreed among experimenters and ESA that instruments will need aperture doors. Since these have a major influence on the heat management, they are to be considered as part of the heat shield. In this way, all instrument aperture thermal designs can be managed by the heat shield system.

The entrance aperture sizes of instruments are a general concern, because for each instrument there are minimal aperture size requirements to fulfill their science performance (see paragraph 3.2.1).

The visible-light instrument *VIM* can use a front filter to reject most of the heat by the high reflectivity of the filter.

The EUV imaging telescopes (*EUI*) will use a combination strategy by using a front filter behind a long baffle, limiting the field of view. Further heat will be rejected by the baffle in the first focal plane of the primary mirror of the Gregorian telescope.

For the EUV spectrometer (*EUS*), no entrance filter can be used with the wavelength ranges considered. So, another solution is under study: a visible-light transparent primary mirror with a thin VUV-reflective coating will let pass through the longer wavelengths and, thus, most of the solar heat can be managed behind the primary mirror, preferentially by reflecting it out into space [2].

3.1.2 System designs

All instruments (*VIM, EUI, EUS, COR*) prefer an off-axis telescope design, which obviously makes the heat management inside the instrument easier.

The *VIM* High Resolution Telescope system [3] is an off–axis Ritchey-Chretien telescope feeding a filtergraph to be shared with the Full Disk Telescope. Figure 1 shows a sketch of the possible instrumental design.

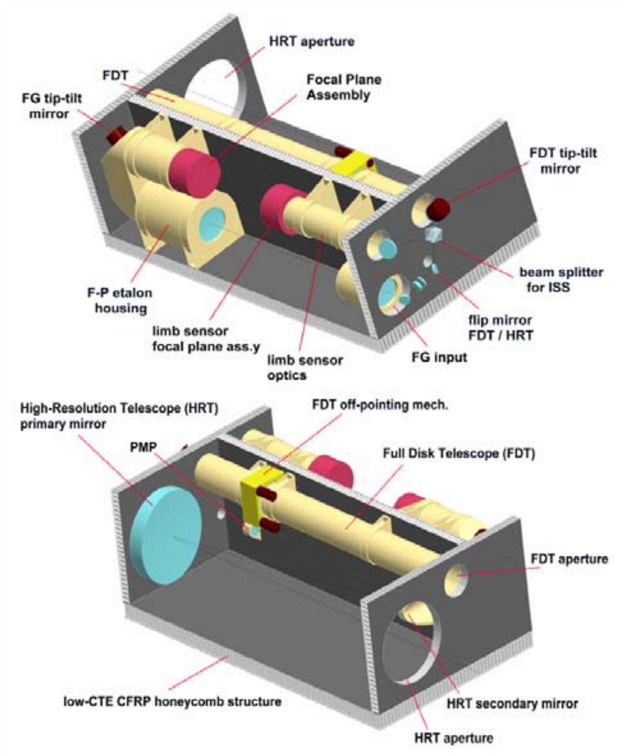

Figure 1: Sketch of the possible layout of the Visible-light Imager and Magnetograph (VIM) instrument (courtesy of H. Hartwig, MPS).

For the filtergraph, to achieve the required spectral resolution, a dual Fabry-Perot etalon, made out of solid lithium niobate wafers, is under study. The solid etalon option requires much less space to fit into the small volume available, while providing a much larger optical acceptance angle than comparable air-spaced etalons [4, 5]. Space qualification of this solution is underway [6].

The *EUI* suite of telescopes can fit into a single, light weight structure. One possible solution, integrating three baffles and sets of mirrors for the HRI and one for the FSI is shown in Figure 2. The detailed description of the instrument and its expected science performance will be given by Hochedez et al. [7].

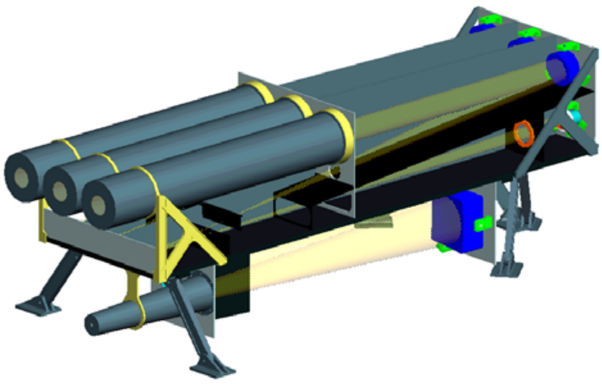

Figure 2: A possible design of the Extreme Ultraviolet Imager (EUI) suite of telescopes, consisting of three high-resolution imagers and one Full Sun Imager(courtesy of F. Auchere, IAS).

Several design options have long been discussed for the EUV spectrometer (*EUS*). Depending on the wavelength range selection, normal-incidence (NI) or grazing-incidence (GI) designs have been under consideration, each with their own advantages and disadvantages. Mainly, the GI option is less vulnerable by contamination and puts less heat density on the optical elements, while the NI option is a simpler optical design with better image quality [8]. Either case applies only for the telescope part, while the spectrograph of the instrument can be conceptually identical. There are already different "precursor" studies underway, where spectrographs of this type have flown or will fly on rocket flight missions. See, e. g., the EUNIS instrument [9] and the RAISE instrument [10]. Each of these spectrometers employ, like it is the baseline for EUS, a toroidal varied-linespace grating [11] because it can provide a good spectral and spatial resolution within a large field of view with only one single reflective element. This ensures a high throughput despite the generally low normal-incidence reflectance of mirrors at these wavelengths. A radiometric efficiency calculation of this design is given by Teriaca at el. [12], showing that efficiency is high enough for spectroscopic line analysis with high-cadence imaging. A preliminary optical design study has shown (see Figure 3) that a design with three wavelengths bands of major scientific importance is possible within the envelope given by the PDD.

3.1.3 Detector development

Although different wavelengths bands require detectors with different technologies, there are some common requirements of the remote sensing instruments:

- Large format sensors: 2k x 2k pixels
- Small pixel size: ~10 µm
- Science-grade dynamic range, noise, linearity, etc.
- EUV, VUV sensitivity
- Radiation hardness
- Low power consumption

The requirements call for CMOS-APS devices which are in some form already commercially available but either not sensitive in the required wavelength band or not space qualified (mostly both). Several approaches have been made to overcome these difficulties and four developments are being followed in parallel:

1. Large format, *back-thinned APS* devices have been developed at E2V (UK) with Rutherford Appleton Laboratory (RAL). They have been tested in the near UV but their EUV performance is to be shown.
2. For VUV instruments *intensified APS* cameras are being developed by several groups. These are using CMOS-APS sensors coupled to a micro channelplate intensifier (MCP). In this case the APS sensor only needs sensitivity at visible wavelengths while the VUV sensitivity is given by the photocathode of the MCP (see Teriaca et al. [12]).
3. For the EUV wavelengths of the EUI channels it is possible to use a *scintillator coating on the CMOS-APS sensor*. The first such camera will be used for the SWAP instrument of ESA's PROBA2 mission [13].

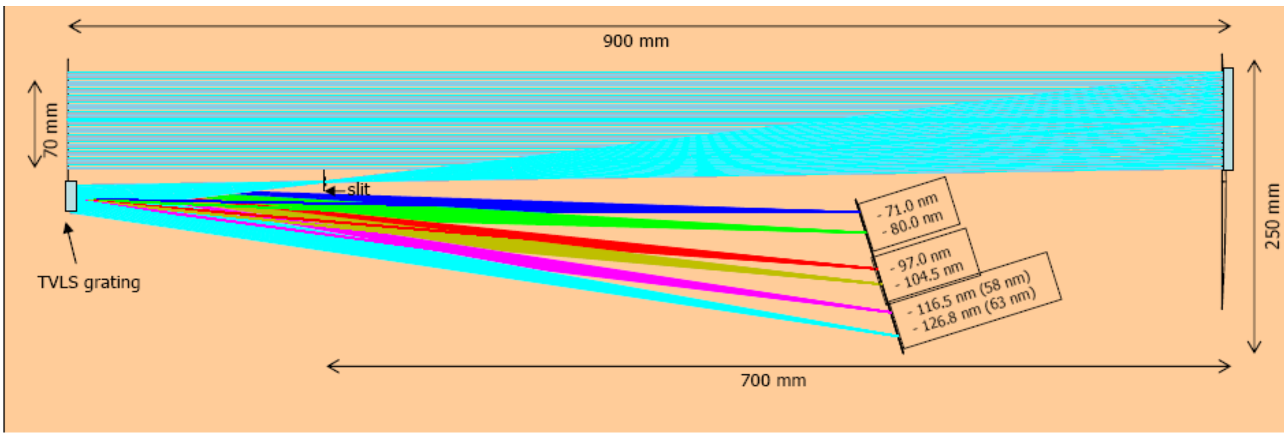

Figure 3: Optical design of a possible Extreme Ultraviolet Spectrometer (EUS) with three wavelength ranges between 71 nm and 127 nm.

4. One alternative ultraviolet imaging device can be a *wide bandgap detector*. Called “Blind to Optical Light Detectors” (BOLD), their development is now funded by ESA. However, the development is time critical as the status of these sensors is least mature among these four options. On the other hand, the wide bandgap detectors seem to be ideal for Solar Orbiter ultraviolet instruments due to their unprecedented advantages:
    - Due to their insensitivity to the visible and NIR solar radiation (solar blindness), less filters are needed (effective area increased, cost & risk reduced).
    - Due to EUV/VUV sensitivity no more MCP are needed (high voltage, gain depression avoided).
    - They can be operated at high temperatures without cooling (smaller radiators needed, no cold traps for contaminants). As a result, they are expected to be more sensitive, have better uniformity, and be more stable.

All of these sensors available today are based on 1kx1k format, and the space qualified 2kx2k device is not yet commercially available.
In summary one can state that solutions for the focal plane units are already very closely available, but much more research and development is necessary to build the cameras required for Solar Orbiter.

3.2 Open technical issues

3.2.1 *Aperture size*s
To fulfil the science performance requirements, most remote sensing instruments need larger aperture sizes than initially given in the early PDD versions, due to diffraction limitation or radiometric reasons mainly driven by image cadence and signal to noise ratio:

- *VIM* needs aperture size of 16 cm by diffraction limitation and signal to noise constraints of the polarization measurements.
- The EUI channels need at least 3 cm aperture sizes for radiometric reasons. The Lyman-α channel needs at least 3 cm (to achieve 1" resolution per 2 pixels) due to diffraction limitation. A size of 6 cm would be required to reach the pixel limited resolution (0.5" per pixel) of the other EUV-HRI channels.
- *EUS* needs 7 cm for radiometric reasons.

The large aperture requirements are directly affecting science performance and, therefore, technical solutions must be found to limit the heat load entering through these openings.

3.2.2 *Filter and mirror coatings stability*
The extreme environmental conditions of the mission, in particular related to the thermal, energetic particle, and cleanliness conditions require studies on coating stability and degradation of mirrors and filters. Specifically, there are the following items of concern:

- VIM’s large entrance filter
- VIM’s LiNbO3 etalon
- EUI’s thin metal foil filters
- EUV multilayer mirror coatings
- EUS’s and COR’s primary mirror coatings (thin coatings or multilayers)
- Contamination of exposed optical surfaces under intense UV irradiation.

First positive results have already been reported with regard to stability of multilayer coatings under Solar Orbiter conditions [14]. Further studies are foreseen towards a full qualification of these items.

3.2.3 *Data compression*
The high spatial resolution obtained at the close proximity of observation requires a large data rate, in clear contradiction to the limitations imposed by the mission orbit. Observations must make use of data compression schemes with high compression factors. Different options exist for the magnetographic and the spectrographic data than for the pure image data to reduce data volume. As an example we show in Figure 4 a raster scan image taken with the SUMER spectrograph aboard SOHO in the transition region line Si IV at 139.4 nm, with a resolution of about 1.5 arcsec.

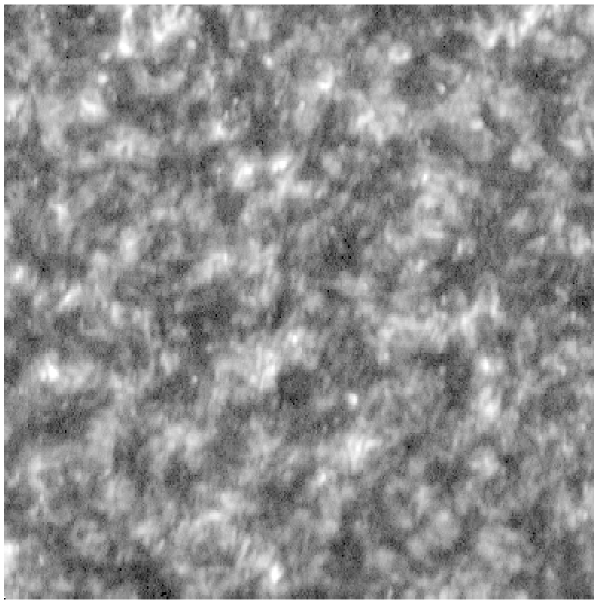

Figure 4: Raster scan image of a transition region area of 300” x 300” in the Si IV 139.4 nm line observed by SUMER on board SoHO

The data have been compressed on board by a Gaussian line fitting routine to transmit only three line parameters (first three moments of the profile). The spectrograph on Solar Orbiter must make use of similar compression schemes, in order to maximize the scientific data volume to be gained during an encounter period. Many ways of data compression are already under investigation, including the employment of commercial image compression schemes (like, e. g., novel JPEG schemes). However, to avoid unnecessary loss of information, more studies are required to fully exploit each instrument's optimal ways of onboard processing and compression of data.

4 CONCLUSIONS AND OUTLOOK

We have shown that the experimental approaches to achieve the goal of Solar Orbiter, to explore the energetics, dynamics, and fine-scale structure of the Sun's magnetized atmosphere have already been well addressed by instrument's consortia. Technical challenges of the mission have been identified and some useful solutions have been found to cope with constraints and limitations imposed by the mission's design. Remote sensing instrumentation of the 1m-class with 1 arcsec resolution will clearly make significant progress in achieving this goal. Structures in the solar transition region as seen in Figure 4 are clearly not resolved. Depending on the spectral coverage of the suite of remote sensing instruments, Solar Orbiter will bring us much closer to the scene of the energetics and dynamics of the solar atmosphere from the photosphere to the corona.

ACKNOWLEDGEMENTS

Many contributions for this presentation came from partners of the VIM, EUI, EUS consortia. I am grateful for all discussions held with all partners in these groups. Among all colleagues I would like to thank for their contributions Luca Poletto, Kevin Middleton, Roger Thomas, Don Hassler, Valentin Martinez Pillet, Jean-Marc Defise, Ali BenMoussa, and Luca Teriaca.

REFERENCES

1. R. A. Harrison, "Report on the Solar Orbiter Working Group Activities: Remote Sensing", *ESA SP-641,* S0.3, these conference proceedings.
2. U. Schühle, H. Uhlig, W. Curdt, T. Feigl, A. Theissen, L. Teriaca, "Thin silicon carbide coating of the primary mirror of VUV imaging instruments For Solar Orbiter", *ESA SP-641*, Poster P.36, these conference proceedings.
3. S.K. Solanki, V. Martinez Pillet, and the VIM Team, "A possible configuration of the Visible-light Imager and Magnetograph on Solar Orbiter", *ESA SP-641*, Poster P.51, these conference proceedings.
4. V. Martinez Pillet, A. Alvarez-Herrero, G. Ramos, L. Jochum, E. Ballesteros, J.L. Medina Trujillo, T. Belinguer, Lithium niobate etalons for space applications, *ESA SP-641*, Poster P.36, these conference proceedings.
5. C. Trosseille, T. Appourchaux, V. Martinez-Pillet, et al., „Spectral Analyzer of the Velocity and Imaging Magnetograph of the Solar Orbiter Mission“, *ESA SP-641*, Poster P.55, these conference proceedings.
6. U. Schühle, S. K. Mathew, M. Wedemeier, H. Hartwig, E. Ballesteros, V. Martinez Pillet, S. K. Solanki, "Space qualification of a thin wafer lithium niobate etalon for the Visible light Imager and Magnetograph (VIM)", *ESA SP-641*, Poster P.50, these conference proceedings.
7. J.F. Hochedez, T. Appourchaux, J.-M. Defise, L.K. Harra, U. Schühle and the EUI consortium, "EUI, the ultraviolet imaging telescopes of Solar Orbiter", *ESA SP-641*, S6.1, these conference proceedings.
8. K. Middleton, V. Da Deppo, L. Poletto, U. Schühle, R.J. Thomas, P.R. Young., "Optical Design of the Extreme Ultraviolet Spectrometer (EUS) on Board Solar Orbiter", *ESA SP-641*, S7.5, these conference proceedings.
9. D.M. Rabin, R.J. Thomas, J.M. Davila, J.W. Brosius., "First Results from EUNIS-06", *ESA SP-641*, Poster P.44, these conference proceedings.
10. D.M. Hassler, C.E. DeForest, S. McIntosh, D. Slater, T. Ayres R.J. Thomas, U. Schühle, H. Michaelis, H. Mason, "Developing Next Generation Spectrograph Technology for Solar Orbiter with the Rapid Acquisition Imaging Spectrograph (RAISE) Sounding Rocket Program", *ESA SP-641*, Poster P.24, these conference proceedings.
11. L. Poletto, R.J. Thomas, "Stigmatic spectrometers for extended sources: design with toroidal varied-linespace (TVLS) gratings", *Appl. Opt.*, Vol. 43, 2029, 2004.
12. L. Teriaca, U. Schühle, W. Curdt., "Design and expected efficiency of an imager and a spectrograph at the H I Lyman Alpha line", *ESA SP-641*, Poster P.54, these conference proceedings.
13. J.-M. Defise, D. Berghmans, J.-F. Hochedez, J.-H. Lecat, E. Mazy, P.L. Rochus, T. Thibert, P. Nicolosi, M.G. Pelizzo, U. Schühle, R. Van der Linden, A.N. Zhukov, "SWAP: Sun watcher using APS detector on-board PROBA-2, a new EUV off-axis telescope on a technology demonstration platform", *Proc. SPIE,* 5171, 143-154, 2004.
14. A.D. Rousseau, D.L. Windt, B. Winter, et al., Stability of EUV multilayers to long-term heating and to energetic protons and neutrons for extreme solar missions, *Proc. SPIE*, 5900, 1 - 9, 2005.