Proposal for the Construction of a

Solar Chromospheric Detector

for the Astronomical Institute of the

Slovak Academy of Sciences

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1. Introduction

The High Altitude Observatory (HAO) of the National Center for Atmospheric Research (HAO) is proposing to construct a Solar Chromospheric Detector (SCD) instrument to be operated on one of the 20 cm Zeiss coronagraphs at the Lomnický Štít Observatory. The SCD instrument will be capable of observing the solar disk and prominences above the limb in a variety of absorption and emission lines ranging in wavelength from 588 nm to 1083 nm. It will enable measurements of the complete polarization state across these solar lines providing information on the velocity field and vector magnetic field in the solar chromosphere.

This document is intended to provide a detailed description of technical specifications, and a Statement of Work to complete the design and construction of the SCD. The remaining sections of this document discuss:

2. SCD goals and capabilities
3. Properties of the 20 cm Zeiss coronagraph
4. Conceptual design of the SCD
5. Estimate of SCD cost and schedule
6. Detailed list of deliverables
7. HAO Statement of Work

2. SCD goals and capabilities

The solar chromosphere derives its importance as the interface between the gas dominated photosphere and the magnetism dominated corona. Observing the chromosphere is essential to understand the mass and energy balance of the outer solar atmosphere and the origins of solar activity. Over 90% of the non-radiative energy of the solar atmosphere is deposited in the chromosphere and it is the probable source of the mass flux into the corona. The chromosphere is a highly dynamic region of the solar atmosphere, which is not governed by local thermodynamic equilibrium. Observations of this region must be accomplished at a high cadence, of order 10 seconds, in order to capture the dynamic phenomena such as waves and shocks. Also, the chromosphere is structured on very fine spatial scales, so observations should be taken with at least one arcsecond sampling.

Understanding this complex region requires observations of the Doppler shift and polarization of light in solar absorption and emission lines formed throughout this region of the atmosphere. The required high time cadence points towards a filter-based instrument because a slit spectrograph is not capable of scanning the field at the required 10 second cadence. The filter must be highly wavelength diverse and capable of observing in a number of chromospheric lines over a broad wavelength range. We propose that the SCD should be a combination polarimeter and narrowband tunable filter that follows from the heritage of the Coronal Multi-Channel (CoMP) instrument and the CoMP-S instruments operating on Mauna Loa, Hawaii and Lomnicky Peak, Slovakia. The SCD will be able to measure the Doppler shift and complete polarization state of absorption and emission lines across a wide range of the solar spectrum, observing radiation from the solar disk and above the limb. Placing it behind one of the 20-cm Zeiss coronagraphs at the Lomnicky Peak Observatory will allow it to obtain observations at the diffraction limit of that coronagraph, with better than one arcsecond imaging in the visible region of the solar spectrum.

3. Zeiss 20-cm Coronagraph

The coronagraph which will be used in this project is one of the dual Zeiss coronagraphs at the Lomnický Štít Observatory. The coronagraph objective has an aperture of 20 cm and a focal length of 3 m. Reimaging optics produce a final focal length of 4 m (4.1 m and f/21 at 656 nm). Information on the optics was imported into the Zemax optical design software package and used to produce the ray trace of the back end of the coronagraph shown in Figure 1. The corresponding spot diagram (Figure 2) shows that the coronagraph achieves diffraction limited performance between 588 and 1083 nm. The spot diagrams at the three wavelengths were obtained by shifting the focus of the objective lens while keeping all of the subsequent optics and focal plane fixed. There is an existing mechanism to shift the focus of the objective lens that is under manual control. This motion will need to be automated to move the objective lens when different wavelength regions are observed.

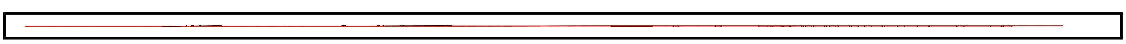

Figure 1. Ray trace of the back end of the Zeiss 20 cm coronagraph. In addition to the field lens and the re-imaging lens pair, three lenses surround the Lyot stop. The calibration optics, narrow band prefilter, and the 5 stage Lyot filter are between the reimaging lens and the image. These optical elements can be mechanically offset from the main optical axis to view any part of the Sun from 0.0 to 0.32 degrees from Suncenter.

The optical properties of the Zeiss coronagraph derived from the optical design are listed in Table 1. The resolution is the diffraction limited spatial resolution in arcsec and microns projected in the focal plane, defined as the Airy disk radius ($=1.22\lambda/D$). The coronagraph optics limit the available field to <0.49 degrees from disk center.

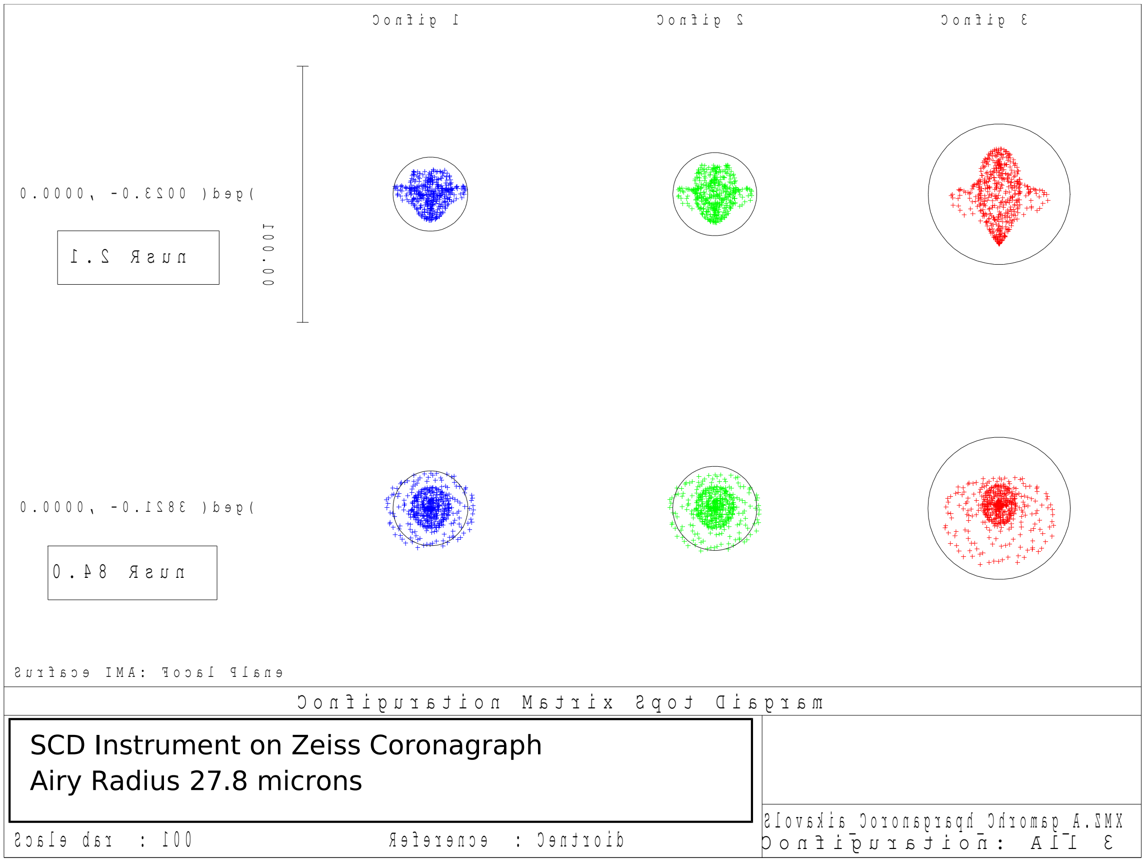

Figure 2. Spot diagrams for the Zeiss coronagraph indicating diffraction limited performance at wavelengths of 588, 656 and 1083 nm (blue, green red) at the solar limb (top row) and at the outer edge of the FOV (bottom row). The Airy disks are shown by the circles.

Assuming the image scale at H-alpha of 50.2 arcsec/mm and assuming an Andor SCMOS detector with 2560 x 2120 pixels of 6.5 microns size gives a field-of-view (FOV) at the camera of 835 x 692 arcseconds or 0.87 x 0.72 solar radii (assuming 960 arcsec per solar radius). This is nearly identical to the FOV of the CoMP-S instrument. This pixel size allows at least critical sampling of the Airy disk at all wavelengths. The relative size of the solar disk and the SCD FOV are shown in Figure 3.

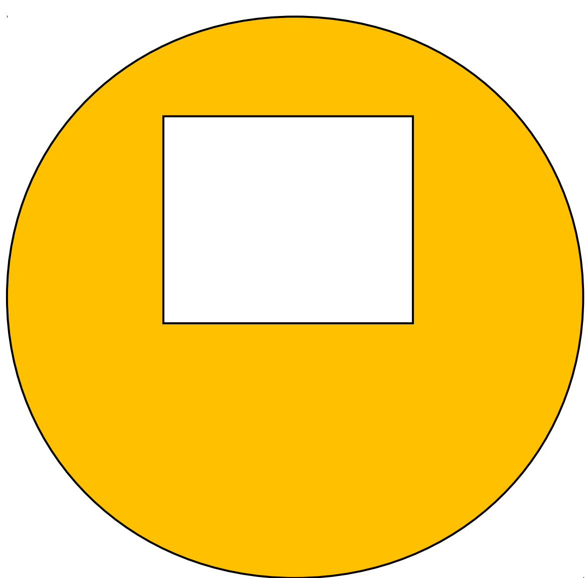

Figure 3. Diagram showing the relative size of the Sun and the field-of-view of the SCD.

Table 1. Zeiss Coronagraph Optical Properties

Wavelength (nm)	Focal Length (mm)	Image Scale (arcsec/mm)	Resolution (arcsec)	Resolution (microns)
588	4089	50.4	0.74	15.1
656	4106	50.2	0.82	16.4
10830	4217	48.9	1.36	27.8

4. Conceptual Design of the SCD

As justified in section 2, the SCD will be a combination tunable filter and polarimeter. It will derive its heritage from the CoMP and CoMP-S instruments (Tomczyk et al., 2007), but it will differ significantly from these instruments in two important aspects. First, the CoMP instruments were specifically designed to observe the solar corona. For coronal observations, a two-beam instrument is required in order to remove the effects of aerosols in the Earth's atmosphere. Since the SCD will observe the much brighter chromosphere, dual-beam observations are not required and the SCD will be a single beam instrument. Second, the chromosphere is much cooler than the solar corona. Therefore, its absorption and emission lines are significantly narrower in wavelength. Casini (2007) has computed that in order to observe the polarization signatures in the chromosphere, a spectral resolution of 0.046 nm is required for observations of the HeI 1083 nm line and a spectral resolution of 25 pm is required for observation of the HeI 587.6 nm line. Then, the birefringent filter for the SCD will need to have a finer spectral resolution that the CoMP instruments by a factor of about three.

The central component of the SCD will be a tunable filter and polarimeter. The polarimeter will consist of two Ferro-electric Liquid Crystals (FLCs), a fixed retarder and a polarizer. These so-called "poly-chromatic" modulators have been shown to be capable of observing the complete Stokes vector of radiation with near optimal efficiency over a very wide wavelength range (Tomczyk et al., 2010). Also, the FLCs can change state very quickly. The filter will be a five-stage, wide-field calcite birefringent filter with a thickness of the calcite chosen so as to achieve the required spectral resolution of 0.046 nm at 1083 nm. The filter FWHM and free spectral range are shown as a function of wavelength in Figure 4. The thinnest stage of the filter will contain 4 mm of calcite and the thickest stage will have 64 mm of calcite. This is compared to the CoMP instruments which have 22 m of calcite in their thickest stages. As before, the wavelength selection will be accomplished with five Nematic liquid crystals. The polarizers will be obtained from CODIXX and the super-achromatic retarders will be obtained from Astropribor as were successfully demonstrated in the CoMP-S.

Temperature control of the birefringent filter will be provided by an ILX Lightwave temperature controller. This has demonstrated temperature stability of a few mK in the CoMP. Optical components will be held with aluminum hexagonal holders in order to maintain precise rotational orientation. The filter optical elements are coupled with index matching oil and bracketed by windows with AR coatings on the outside surfaces to reduce reflective losses.

The baseline detector for the SCD is an Andor sCMOS camera with a format of 2560 x 2160 pixels of 6.5 microns size. The camera has 1.5 electrons readout noise (rolling shutter) and 2.5 electrons (global shutter) and has a maximum frame rate of 30 frames per second. The spectral region will be selected with pre-filters with a width dictated by the free spectral range shown in the lower panel of Figure 4. The SCD will have a filter wheel containing 9 pre-filters. Target lines for the SCD might include, but are not limited to the chromospheric lines of HeI 587.6 nm, NaI 589.2 and 589.6 nm, HI 656.3 nm, CaII 854.2 nm and HeI 1083.0 nm. The SCD should also include some photospheric lines to allow observation of the magnetic field in regions below the chromosphere. Appropriate photospheric lines could be FeI 617.3 nm or the line pair of FeI at 630.15 and 630.25 nm. Observation of the continuum will be possible.

A concept diagram of the SCD instrument is presented in Figure 5. Figures 6-8 show the mechanical concept for the SCD. The instrument will be designed both mechanically and electrically to be rotated a full 360 degrees behind the Zeiss coronagraph.

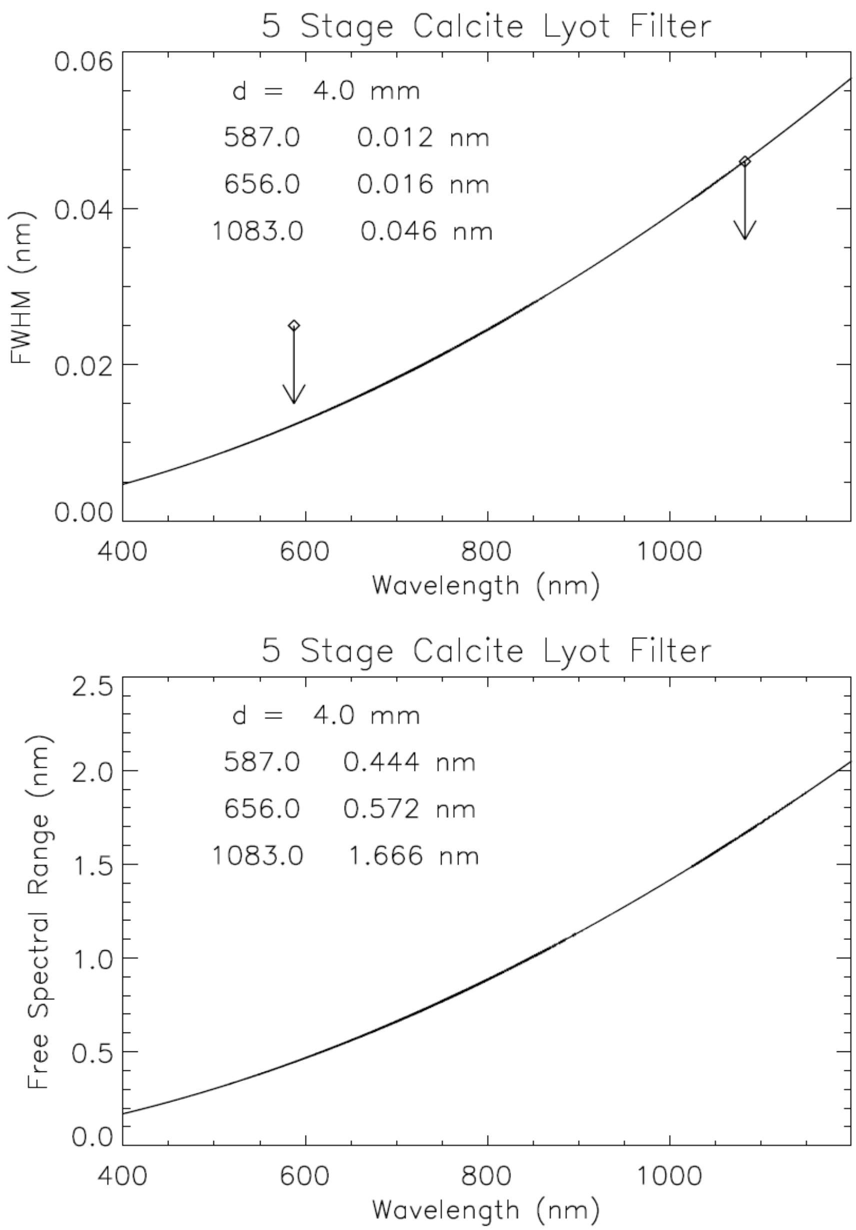

Figure 4. The SCD filter FWHM and free spectral range. The required upper limits on the required filter resolution are shown as the triangles and arrows of the top plot.

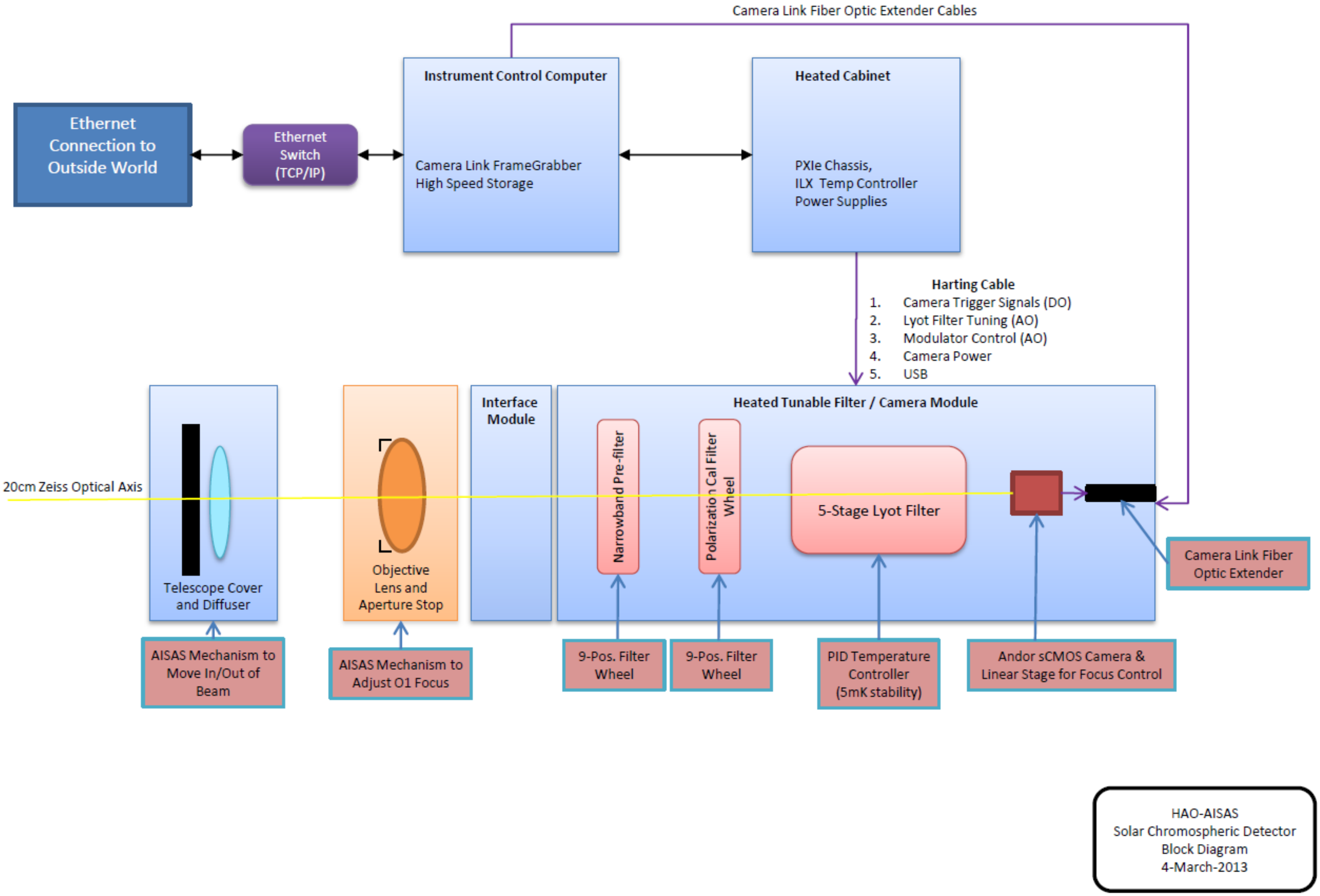

Figure 5. Top Level Concept Diagram of the Solar Chromospheric Detector

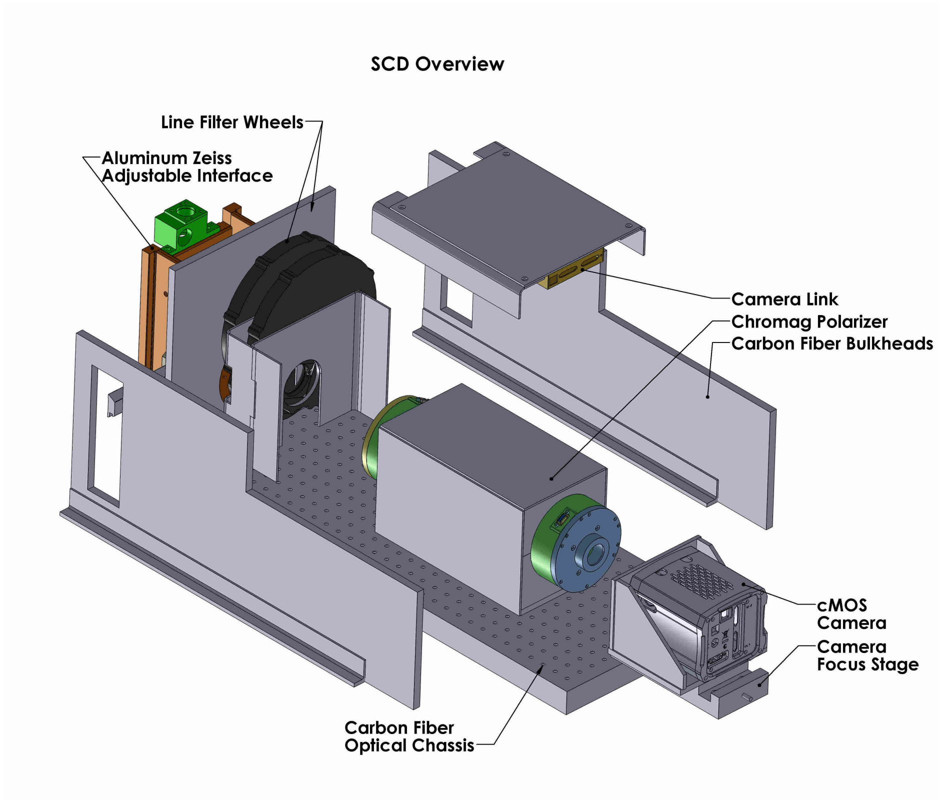

Figure 6. SCD Mechanical Overview

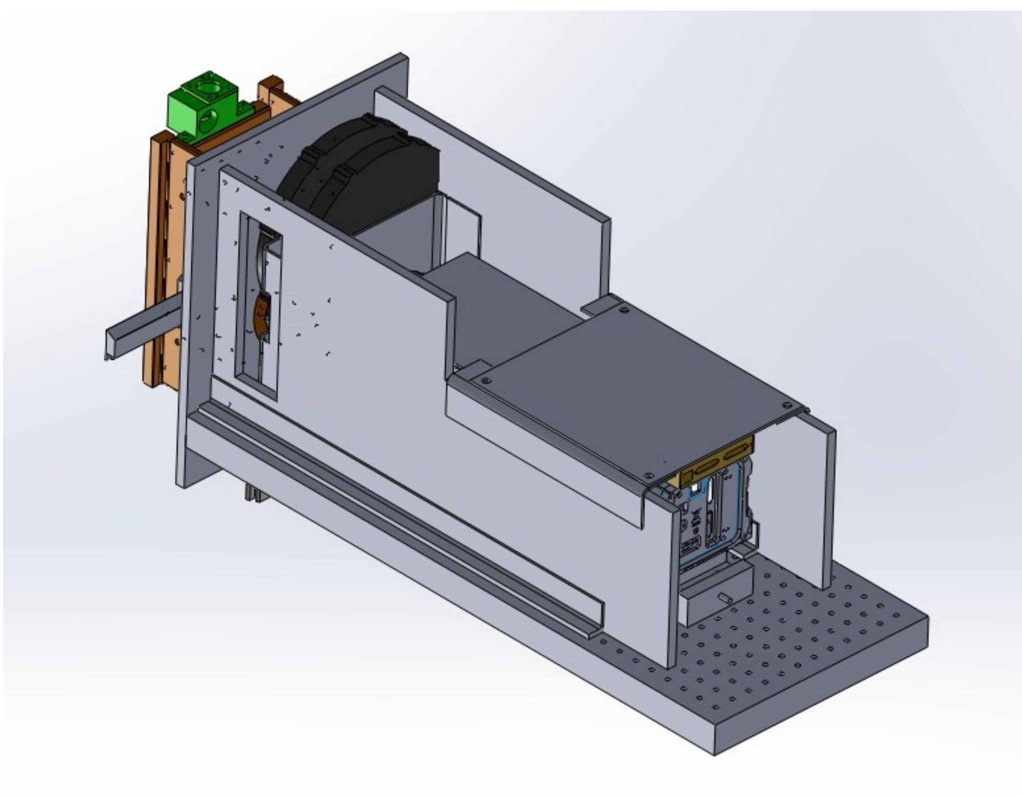

Figure 7. SCD Form Factor

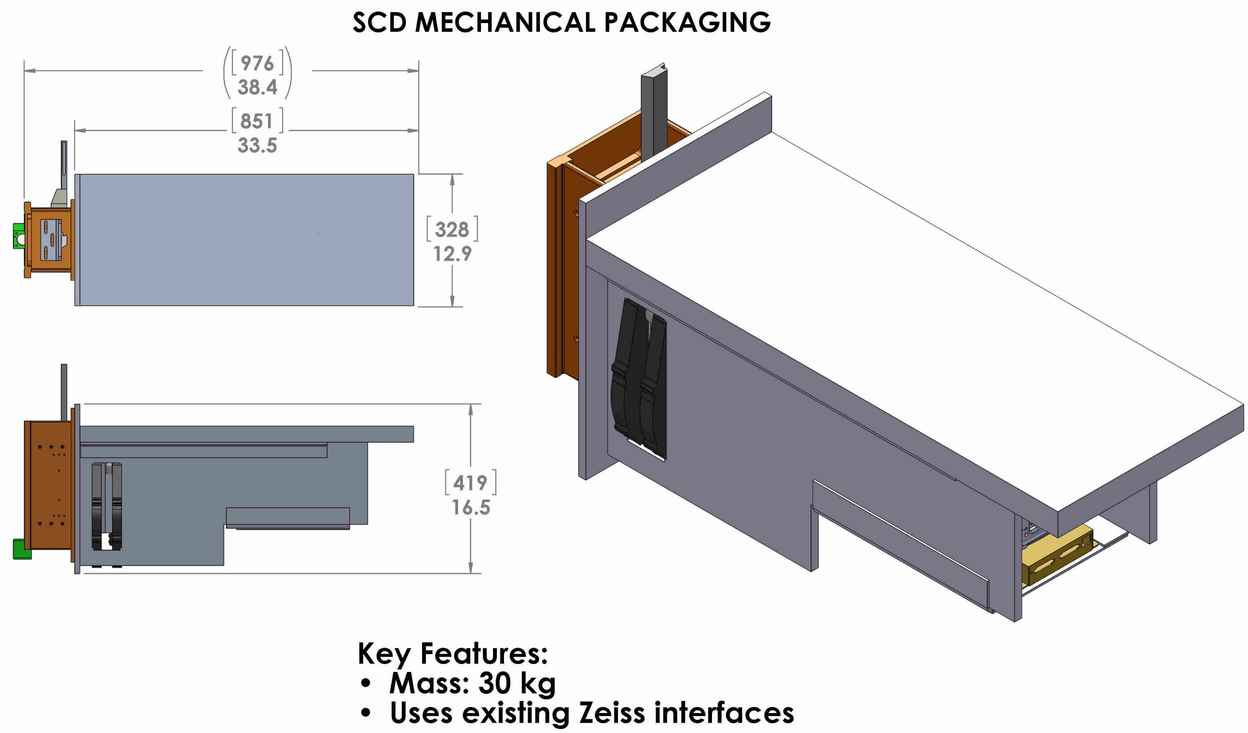

Figure 8. SCD Dimensions and Key Features

5. Cost and Schedule for the SCD

The cost of the SCD will be 500,200 EUR without VAT.

The cost of the SCD includes:

All materials and labor for construction.

Delivery of the instrument by HAO at Stará Lesná.

The SCD instrument is a unique instrument which will require 18 months to design, fabricate and deliver from the date of signing of the contract.

6. Deliverables

Power: AISAS will provide 24V DC on the telescope for emergency heating and 220VAC 50 Hz will be provided in the vicinity of the telescope for peripherals. AISAS will provide UPS with generator backup, but prolonged power outages may occur and need to be accommodated.

Coronagraph: AISAS will provide computer controlled mechanisms to 1) focus the objective lens, and 2) rotate the back end (barrel) of the coronagraph. HAO will build the SCD-Zeiss interface module identical to that produced for the CoMP-S instrument. The

SCD cross section will conform to the existing cross section of the translating section out to a point that includes the re-imaging lens.

Filter/Polarimeter: HAO will provide the filter/polarimeter which will operate over a wavelength range from 588 to 1083 nm. It will be electro-optically tuned with the emission line chosen by interference filters in a 9-position filter wheel. The SCD instrument section containing the filter wheels and polarimeter will be removable from the coronagraph in case of a prolonged power outage. HAO will maintain the temperature of the SCD enclosure including filter/polarimeter and filter wheels at 23 C within 1 C, and the filter/polarimeter at a temperature of 35 C within 5 mC.

Filter Wheels: HAO will provide 2 filter wheels with optical elements. The first will contain 9 interference filters for emission line selection. The second will contain: a dark position, an open position, 4 or 6 polarizing elements for calibration, and a lens which will exchange the image of the field at the focal plane with an image of the objective.

Detector: HAO will provide 1 Andor Neo sCMOS detector with 2560x2160, 6.5 micron pixels. The detectors will have sufficient degrees of freedom to be focused, centered and adjusted normal to the beam. The detector will communicate with the instrument control computer through optical fiber cables with cables and extenders provided by HAO. The detector will be mounted in a way that will allow easy removal and replacement or upgrade.

Computer: The instrument control computer will be provided by HAO. It will include a monitor, USB keyboard and USB mouse, and will operate on 220 V. The observing program will be written in LabView operating under Windows 7 (64-bit). The computer will have at least 2TB disk storage. The computer will be mounted in a 19” rack provided by AISAS. The computer will communicate using RS-232 with AISAS mechanisms to: 1) move the focus of the objective lens, 2) rotate the coronagraph barrel, 3) open close the coronagraph lens cover.

Software: HAO will provide instrument control software including source code.

Heated Cabinet: The National Instruments PXIe chassis, ILX temperature controller, and power supplies will be provided in a heated cabinet to be mounted at the base of the Zeiss coronagraph. A Harting cable (<7m in length) will be provided which connects this heated cabinet to the SCD instrument module.

Weight and Size: The SCD will weigh less than 30kG and not be longer than 1.1 m.

Documentation: HAO shall provide a complete set of documentation, drawings and software source code with the SCD.

7. Statement of Work

On delivery, HAO shall provide the SCD instrument which includes:

> The filter/polarimeter which can be mounted to the back of one of the coronagraphs at Lomnicky Stit Observatory.

A set of pre-filters in a filter wheel that can be moved into the optical path under computer control for selection of the spectral line to observe.

An additional filter wheel containing: optics for polarization calibration; a dark slide; an open position; and an exchange lens.

A temperature control unit which will stabilize the temperature of the filter/polarimeter to 35 C.

A detector system capable of recording the output of the filter/polarimeter at the required spatial resolution of 1.7 arcseconds and temporal resolution of 10 seconds.

A rack-mounted computer system for control of the SCD system. This includes keyboard, mouse, monitor and 2 TB disk storage.

A set of all necessary cables.

On delivery, HAO will provide a complete set of documentation including:

Manufacturer manuals for all purchased equipment.

SolidWorks engineering drawings for all fabricated components.

Zemax optical design files.

Altium wiring diagrams.

Source code for all software.

LabView software license.

References

Casini, R., “Prominence and Filament Magnetometry Simulations”, COSMO Technical Note #12, 2007.

Tomczyk, S., Casini, R., and de Wijn, A., “Wavelength-diverse polarization modulators for Stokes polarimetry”, 2010, *Applied Optics,* **49**, 3580.

Tomczyk, S., Card, G.L., Darnell, T., Elmore, D.F., Lull, R., Nelson, P.G., Streander, K.V., Burkepile, J., Casini, R., and Judge, P.G., 2007, “An Instrument to Measure Coronal Emission Line Polarization,” *Solar Physics*, **247**, 411.