SUNRISE: High resolution UV/VIS observations of the Sun from the stratosphere

A.M. Gandorfer[a], S.K. Solanki[a], P. Barthol[a],
B.W. Lites[b],
V. Martínez Pillet[c],
W. Schmidt[d], D. Soltau[d]
A.M. Title[e]
and the Sunrise Team

[a]Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
[b]High Altitude Observatory, Boulder, CO, USA
[c]Instituto de Astrofísica de Canarias, La Laguna, Tenerife, Spain
[d]Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany
[e]Lockheed-Martin Solar and Astrophysics Lab., Palo Alto, CA, USA

ABSTRACT

SUNRISE is an international project for the development, construction, and operation of a balloon-borne solar telescope with an aperture of 1 m, working in the UV/VIS spectral domain. The main scientific goal of SUNRISE is to understand the structure and dynamics of the magnetic field in the atmosphere of the Sun. SUNRISE will provide near diffraction-limited images of the photosphere and chromosphere with an unpredecented resolution down to 35 km on the solar surface at wavelengths around 220 nm. The focal-plane instrumentation consists of a polarization sensitive spectrograph, a Fabry-Perot filter magnetograph, and a phase-diverse filter imager working in the near UV. The first stratospheric long-duration balloon flight of SUNRISE is planned in Summer 2009 from the swedish ESRANGE station. SUNRISE is a joint project of the german Max-Planck-Institut für Sonnensystemforschung (MPS), Katlenburg-Lindau, with the Kiepenheuer-Institut für Sonnenphysik (KIS), Freiburg, Germany, the High-Altitude Observatory (HAO), Boulder, USA, the Lockheed-Martin Solar and Astrophysics Lab. (LMSAL), Palo Alto, USA, and the spanish IMaX consortium.

In this paper we will present an actual update on the mission and give a brief description of its scientific and technological aspects.

1. INTRODUCTION: SCIENCE WITH SUNRISE

The solar atmosphere is pervaded by magnetic fields which are at the root of the many fascinating phenomena grouped together under the name solar activity. The magnetic processes that govern solar activity locally determine ‘space weather’ as well as being potentially significant drivers of terrestrial climate variability on a time scale of decades to centuries. If we are to understand these fundamental processes, we must learn how the magnetic field interacts with the solar plasma and must uncover the conversion of energy between its mechanical, magnetic, radiative, and thermal forms. The solar photosphere represents the key interaction region: thermal, kinetic and magnetic energy all are of the same order of magnitude and transform easily from one form into another. The interaction between convection, radiation and magnetic field in the electrically conducting solar plasma leads to the creation of a rich variety of magnetic structure, from huge sunspots down to intense magnetic field concentrations on length scales down to a few tens of km. The wealth of fine-scale structure in the solar photosphere is illustrated in Fig. 1.

Send correspondence to A. Gandorfer
E-mail: gandorfer@mps.mpg.de, Telephone: ++49/5556/ 979 397
Address: Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Strasse 2, D-37191 Katlenburg-Lindau, Germany

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1.1. Science requirements

The resulting science requirements for the SUNRISE instruments are that they should provide images of the magnetic structure and measurements of the magnetic field, the flow velocity, and thermodynamic properties of the plasma...

- ...with a spatial resolution down to $\simeq 35\,\mathrm{km}$ on the Sun,
- ...on a sufficiently large field of view to cover the magnetic connectivity in the solar atmosphere ($\simeq 30\,\mathrm{Mm}$),
- ...over a sufficiently long time to follow the evolution of magnetically active regions (i.e., several days), and
- ...simultaneously in different heights of the solar atmosphere.

This leads to the concept of a diffraction-limited operation of a telescope of 1 m aperture in the visible and UV spectral ranges (down to $\simeq 220\,\mathrm{nm}$), equipped with a filter imager, a polarimetric spectrograph, and an imaging magnetograph, on long-duration stratospheric balloon flights in the framework of NASA's LDB program. Observations from above the ground are mandatory in order to avoid the image deterioration by turbulence in the Earth's atmosphere and to gain access to the solar UV radiation between 220 and 370 nm.

2. OBSERVATIONAL PHILOSOPHY

The SUNRISE postfocus instrumentation consists of 5 units, three out of which are science instruments, the other two are system units for image stabilization and light distribution. The SUNRISE science requirements demand simultanous observations of all three science instruments. This is ensured by ISLID, the Image Stabilization and Light Distribution system of SUNRISE, which will be described in detail below. ISLID contains a fast tip-tilt mirror, which is controlled by a correlating wavefront sensor (CWS), which will be described below. ISLID is based on dichroic beam-splitters, which guide the different wavelength bands to the individual science branches in the most efficient way. Part of the light, which is not used for scientific analysis is fed to the CWS. In this way, simultanous observations are possible with maximum photon flux in each channel. While the technical realisation of the individual science instruments will be described in more detail below, we will list their specific roles here:

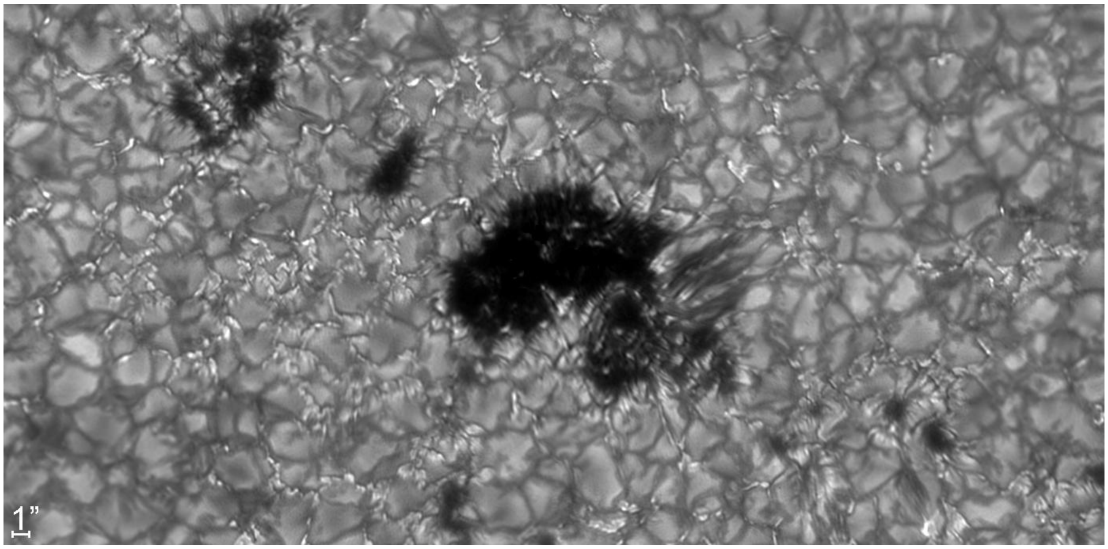

Figure 1. High resolution image of a magnetic solar region observed in the light of the so-called G-band, an absorption band of the CH molecule at 430.5nm. In this wavelength band the small scale manifestations of solar magnetism can be seen as bright features with high intensity contrast (image taken by V. Zakharov at the Swedish Solar Telescope on La Palma, Spain).

a) SUFI

The Sunrise Filter Imager (SUFI) samples the photosphere and chromosphere in distinct wavelength bands. The channel at 225 nm allows studies of the upper photosphere and lower chromosphere at a spatial resolution of 0.05 arcsec (35 km on the Sun). At the same time, this wavelength is important for the stratospheric ozone household. The OH-band at 313 nm and the CN-band at 388 nm provide high contrast, and thus sensitivity to thermal inhomogeneities in the photosphere. The Mg II k line (singly ionized magnesium) at 279.6 nm is an excellent thermometer for the chromospheric temperature structure.

b) SUPOS

The achievement of the main science goals of SUNRISE depends on quantitative and accurate measurements of the strength and orientation of the magnetic field with appropriate spatial, spectral, and temporal resolution. The Sunrise Polarimetric Spectrograph (SUPOS) allows high-resolution vector-polarimetry, simultaneously providing photospheric and chromospheric magnetic field measurements.

c) IMaX

The Imaging Magnetograph EXperiment for Sunrise (IMaX) is an imaging vector magnetograph based upon a tunable narrow-band filter. The instrument will provide fast-cadence two-dimensional maps of the complete magnetic vector, the line-of-sight velocity, and continuum frames with high spatial resolution.

IMaX images will be taken in two to four narrow wavelength bands in either wing of the photospheric spectral line of FeI (neutral iron) at 525.06 nm.

3. INSTRUMENT DESCRIPTION

3.1. SUNRISE Telescope

The SUNRISE telescope is a light weight Gregory-type reflector with 1 m clear aperture and 25 m effective focal length. The main mirror with a parabolic surface and focal length of 2.5 m is an extremely light-weight Zerodur mirror currently being manufactured under responsibility of SAGEM, France, under contract with the german Kayser-Threde company. In the real primary focus a field stop is placed, a heat rejection wedge with a hole that defines the useable field of view, corresponding to 148 000 km on the solar surface. The field stop reflects 99% of the incoming light out of the telescope. This reduces the heat load on the focal-plane instrumentation to about 10 W. The light passing through the field stop is reflected off M2 and folded back by two flat mirrors M3 and M4 to feed the focal-plane package. The latter is mounted piggy-back on the telescope structure and consists of the science instruments and the wavefront sensor/correlation tracker unit. A tip-tilt steering mirror is controlled by the correlation tracker and provides precise pointing and guiding. Stray light is minimized by covering the telescope structure with MLI from both inside and outside, by a set of baffle rings, and by a conical primary-mirror-bore baffle.

The optical system of the SUNRISE telescope is semi-active: relative alignment of M2 to M1 is controlled by low order wavefront sensing in the science focus and passing control signals to the M2 mount. This technique is also used for focusing. The telescope will be built by Kayser-Threde (Munich) under supervision of the Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany. A detailed description of the telescope can be found in Bittner at al., Proc. SPIE 5489, 927.

3.2. Image Stabilization and Light Distribution System: ISLID

ISLID performs two main tasks: First, it forms a real image of the telescope aperture on a fast tip-tilt mirror, which is used to stabilize the image and compensate for residual image motion due to gondola shake and vibrations within the system. This is done with a field lens in the telescopes secondary focus. In order to allow for the UV part of the solar spectrum to be transmitted the lens is made from fused silica and is uncoated. Reimaging is achieved with a two mirror arrangement (for SUFI) and additional refractive optics for SUPOS, IMaX, and CWS.

The second task of ISLID is the light distribution to the different post-focus instruments in a most photon efficient manner by guiding only the dedicated wavelength bands of the instruments by the use of dichroic beam splitters.

3.3. Correlating Wavefront Sensor: CWS

The CWS is used in two ways, for precision images stabilization and guiding, and to control proper alignment of the telescope.

Guiding is performed in a closed-loop servo system that consists of a correlation tracker (CT) to provide the error signal and a tip-tilt mirror performing the correction.

A wavefront sensor measures the actual state of the optical alignment and generates an appropriate error signal.

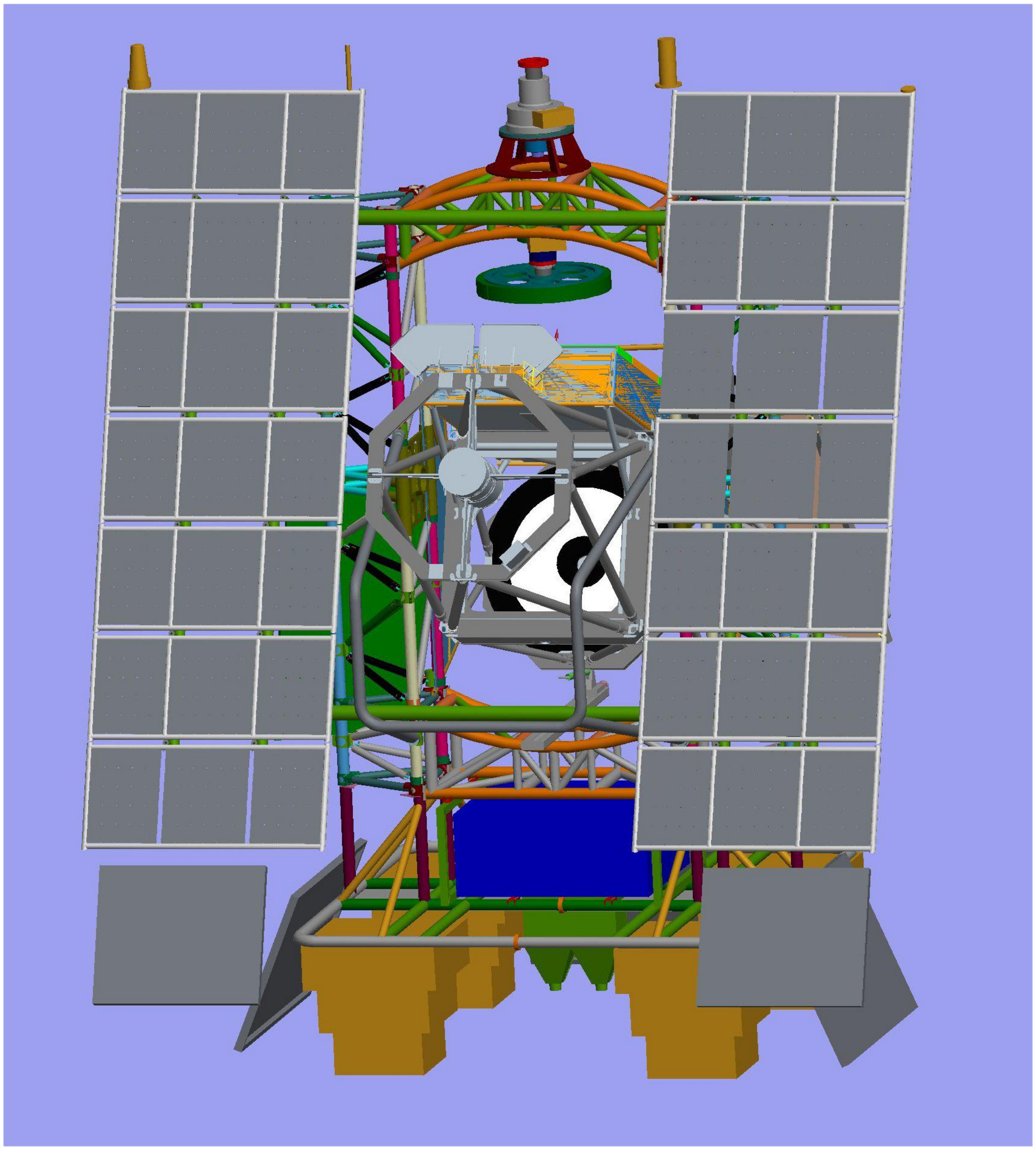

Figure 2. Sketch of the telescope in the gondola with solar panels, landing shock absorbers, and attachment ring to the balloon. The telesope is mounted in an altitude-azimuthal mount. The instrument platform carrying the science instruments is attached to the telescope central frame on top of the telescope. The instrument platform houses all three science instruments (SUPOS, SUFI, and IMaX) as well as the Image Stabilization and Light Distribution system (ISLID) and the Correlating Wavefront Sensor (CWS).

A control system converts this error signal into actuation signals which are used to drive and align the secondary mirror, M2.

The detection principle is based on a correlation tracker generating tip and tilt error signals. However, instead of sensing the position of a single image derived from the entire pupil of the telescope, 18 subapertures sense the local wavefront tilt in two zones of the pupil. The information derived from the 18 independently analysed images of the same solar scene suffices to determine the coefficients of a Zernike function decomposition of the wavefront error up to the third radial degree. The coefficients for tip and tilt, defocus, and Seidel coma are used as error signals for the control system. The system is able to measure and compensate axial and lateral displacement of the secondary mirror, M2, as well as dynamic image displacement errors.

The correlation tracker/wavefront sensor unit including the tip-tilt mirror and the control software is developed by the Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany. For details we here refer to paper 6247-17 by Schmidt et al. in these proceedings.

3.4. SUNRISE Polarimetric Spectrograph: SUPOS

The spectropolarimeter SUPOS has undergone a considerable design change and is now designed as a single spectral line high resolution grating spectrograph working at a wavelength around 854nm. Here a chromospheric line of singly ionized Calcium allows for simultanous magnetic field diagnostics due to its Zeeman splitting. The line is formed in different layers, spanning from the photosphere to the chromosphere. While the interpretation of the data is more demanding as compared to purely photospheric lines, the advantage of having access to chromospheric magnetism more than compensates for this. The full polarisation state of the spectral line will be detected using 2 nematic liquid crystal variable retarders followed by a polarizing beam splitter. The CCD camera is read in synchronism with the electrooptical modulation in order to demodulate the polarization signal.

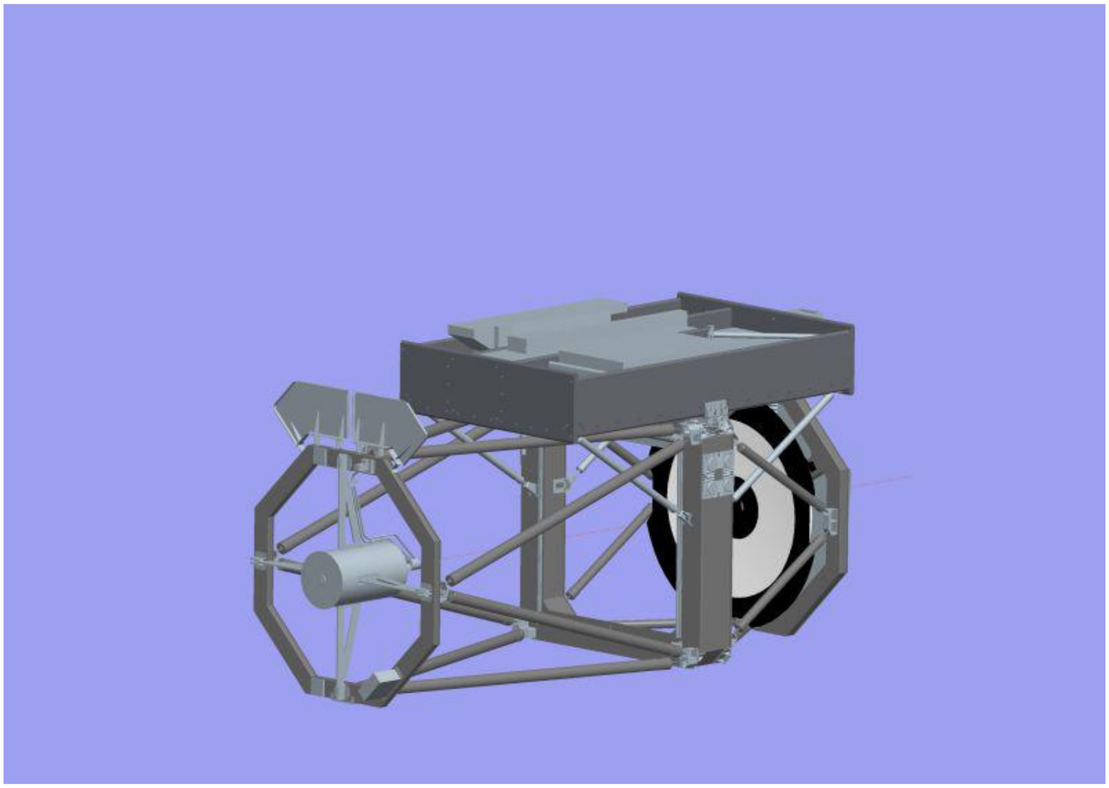

Figure 3. Sketch of the SUNRISE 1 m telescope. The instrument platform is attached to the telescope central frame on top of the telescope. The instrument platform houses all three science instruments (SUPoS, SUFi, and IMaX) as well as the Image Stabilization and Light Distribution system (ISLiD) and the Correlating Wavefront Sensor (CWS).

3.5. SUNRISE Filtergraph: SUFI

The SUNRISE filter imager (SUFI) is the instrument allowing for the highest angular resolution of down to 0.05 arcsec. This corresponds to diffraction limit of the 1m mirror for a wavelength of 225 nm. In order to achieve near diffraction limited imaging, a phase-diverse imaging technique is used by splitting the image in front of the CCD detector: half of the CCD area collects the focused image, while a special optical arrangement forms a second image of the same scene on the second half of the CCD, now with a defocus of one wave. Postfacto restoration of the image free from static aberrations of the optical path can be achieved. The optical arrangement is a Schwarzschild system to magnify the telescope secondary focus by a factor of 5 onto the CCD. SUFI works in distinct wavelength bands in the near UV between 220 nm and 390 nm, which are selected by IAD coated interference filters sitting in a double filter wheel to ensure sufficient blocking against the strong visible and near infrared parts of the solar irradiance.

3.6. Imaging Magnetograph eXperiment: IMaX

IMaX is a polarisation sensitive filtergraph developed for observations of Doppler shifts and polarisation in a Zeeman sensitive spectral line of neutral iron at 525.06 nm.

A tunable $LiNbO_3$ solid state Fabry-Perot etalon is used in double pass. This configuration significantly saves mass and power and relaxes the demanding requirements on passband stability. Since the free spectral range of such a system is quite small, a narrowband interference filter (FWHM 0.1 nm) must be used. Both, prefilter

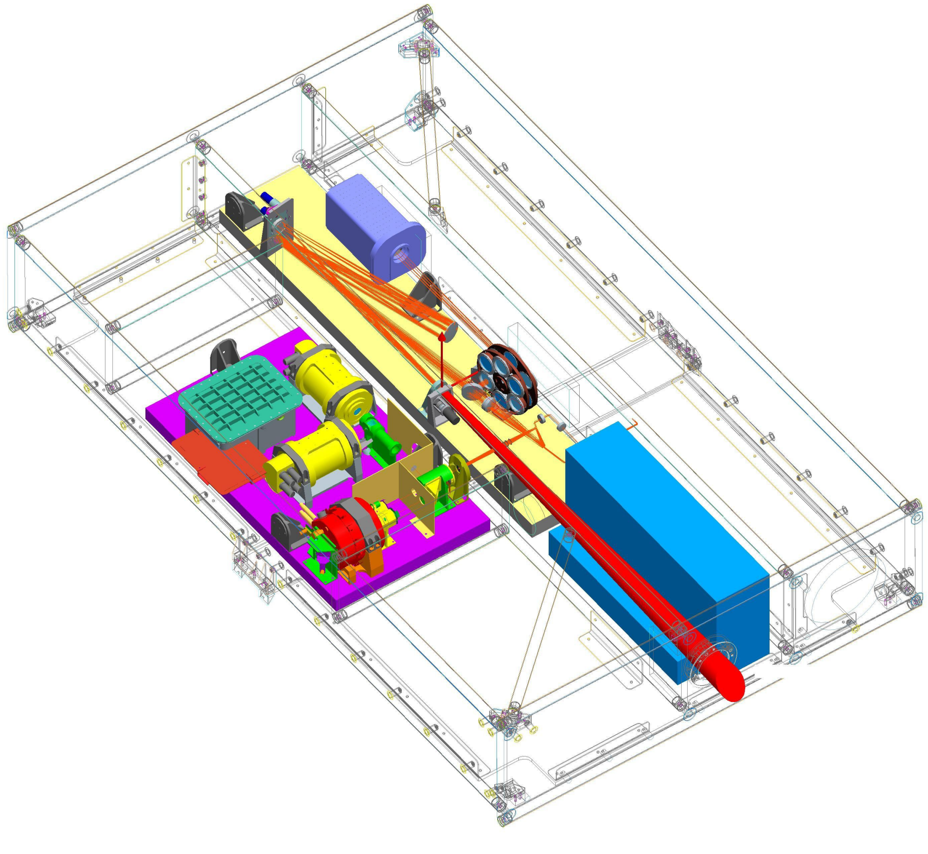

Figure 4. Sketch of the arrangement of the postfocus instrumentation on the instrument platform. The central compartment houses ISLID with the tip-tilt mirror and SUFI with the double filter wheel and the CCD camera. The optical path is sketched. The CWS system is seen as the box on the right side. IMaX is seen to the left. SUPOS is housed in the upper compartment and is omitted in this picture. Light from the main telescope enters from the lower right.

and etalon must be thermally stabilized. For technical details on the Fabry-perot syetm we here refer to the dedicated paper no. 6265-89 by Alvarez-Herrero et al. in these procedings.

Imaging is done with two synchronised CCD cameras for phase diversity reconstruction.

Polarimetry is done with two nematic liquid crystal modulators. Four switching states are needed for full Stokes vector polarimetry. A two-state observing mode is foreseen for longitudinal magnetometry (only circular polarisation).

IMaX is being developed by a Spanish consortium led by the Instituto de Astrofísica de Canarias, La Laguna (Tenerife), in cooperation with the Instituto de Astrofísica de Andalucia, Granada, the Instituto Nacional de Tecnicas Aeroespaciales, Madrid, and the Grupo de Astronomia y Ciencias del Espacio, Valencia.

For technical details on the IMaX instrument we here refer to paper 6265-155 by A. Alvarez-Herrero et al. in these proceedings.

4. BALLOON CONCEPT

The SUNRISE telescope is mounted on the elevation axis to a frame consisting of standard aluminium components. It is designed to withstand the vertical acceleration that is applied to the attachment rings when the parachute is opened near the termination of the flight. This structure and aeroflex shock absorbers protect the payload from the vertical and horizontal components of the landing shock load in case of landing in cross winds. The gondola can be moved in azimuthal direction to point the telescope and the solar panels towards the Sun. This is realized by means of a momentum transfer unit (MTU) mounted at the top of the gondola. The combined structural assembly of gondola, telescope, postfocus instrument platform, as well as solar panels and elecronics racks has been extensively analysed by means of FEM analysis techniques. Thermal analysis of the whole structural assembly has also been performed.

The gondola and the gondola systems (MTU, elevation drive, power supply, coarse pointing, etc.) are responsibility of the the High Altitude Observatory, Boulder, USA.

SUNRISE will be flown in the framework of NASA's LDB (Long Duration Balloon) program. We plan a flight of 4-5 days during summer from the ballooning facilities at ESRANGE near Kiruna, Sweden. The flight trajectory is circumpolar, bound between 68 deg and 76 deg northern latitude. Float altitudes are 35–40 km. Flying during summer from ESRANGE has the advantage of permanent sunlight and small elevation changes of the Sun, so that observation and power generation are uninterrupted; furthermore, the thermal conditions do not vary significantly and the balloon floats at nearly constant altitude. ESRANGE provides excellent infrastructure and allows for long lasting line-of-sight contact to the mission.

Telescope	primary focal length	2.5 m
	effective focal length	25 m
	image scale	8.25 arcsec/mm
Correlating wavefront sensor	wavefront sensor	128 × 128 CCD
	pointing accuracy	$\leq$ 0.01 arcsec
	dynamic range	40 Hz minimum
	number of elements	7
	No. of Zernike terms	5
SUFi	phase diversity imager	
— CCD camera	format	2048 × 2048
	pixel size	12 × 12 μm^2
	FOV (3 pixel sampling)	20 × 40 $arcsec^2$
— phase diversity	beam-splitter, 1 CCD	
— double filter wheel	5 positions	220 nm (continuum) 300 nm (continuum) 313 nm (OH molecular band) 388 nm (CN molecular band) 279.6 nm (Mg II k)
IMaX	polarimetric narrowband imager	
— filter unit	prefilter	narrowband interference filter
	main filter	$LiNbO_3$ Fabry-Perot etalon in double pass
	spectral resolution	4 pm
	spectral line	525.06 nm (Fe I)
— polarimetry unit	polarization modulator	2 nematic liquid crystals, 15 Hz
— Camera	2 CCDs	1024 × 1024
	pixel size	12 × 12 μm^2
	FOV	50 × 50 $arcsec^2$
— phase diversity	2 seperate CCDs	
Spectrograph	focal length	1000 mm
— Scanning unit	step width	0.05 arcsec
	total range	± 50 arcsec
— Main disperser	grating	158 grooves / mm
	spectral resolution	2.7 pm (near 850 nm)
	dispersion	12.6 pm / mm (near 850 nm)
— Polarimetry unit	dual beam system	polarizing beam splitter
	retarder	2 nematic liquid crystals , 16 Hz
— CCD camera	format, speed	652 × 488, 16 frames/s
	pixel size	12 × 12 μm^2
	CCD I FOV	65 arcsec × 0.26 nm
	spectral line	854.2 nm (Ca II)

Table 1. Design parameters of the post-focus instrumentation