The Solar Ultraviolet Imaging Telescope onboard Aditya-L1

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ABSTRACT

The Solar Ultraviolet Imaging Telescope (SUIT) is an instrument onboard the Aditya-L1 spacecraft, the first dedicated solar mission of the Indian Space Research Organization (ISRO), which will be put in a halo orbit at the Sun-Earth Langrage point (L1). SUIT has an off-axis Ritchey–Chrétien configuration with a combination of 11 narrow and broad bandpass filters which will be used for full-disk solar imaging in the Ultravoilet (UV) wavelength range 200-400 nm. It will provide near simultaneous observations of lower and middle layers of the solar atmosphere, namely the Photosphere and Chromosphere. These observations will help to improve our understanding of coupling and dynamics of various layers of the solar atmosphere, mechanisms responsible for stability, dynamics and eruption of solar prominences and Coronal Mass ejections, and possible causes of solar irradiance variability in the Near and Middle UV regions, which is of central interest for assessing the Sun's influence on climate.

Keywords: Solar Astronomy, Aditya-L1, SUIT, solar dynamics, Chromosphere, solar variability

1. INTRODUCTION

Aditya-L1 is India's first multi-wavelength solar observatory in space that aims to provide continuous coverage of the Sun's atmosphere using remote sensing in various wavelength bands[1]. In addition, it will also provide in-situ measurement of particle flux as well as heliospheric magnetic field. The spacecraft will be launched by Polar Satellite Launch Vehicle-XL and will be stationed in a halo orbit around the first Lagrangian point. Aditya-L1 will carry a payload composed of seven instruments, namely, the Visible Emission Line Coronagraph (VELC), the Solar Ultraviolet Imaging Telescope (SUIT), the High Energy L1 Orbiting Spectrometer (HEL1OS), the Soft X-ray Low Energy X-ray Spectrometer (SoLEX), the Plasma Analyzer Package for Aditya (PAPA), Aditya Solarwind and Particle Experiment (ASPEX) and a Magnetometer. Table 1 lists all the instruments onboard Aditya L1 along with their science objectives and the lead institutes. Table 1 shows the spacecraft with the instruments.

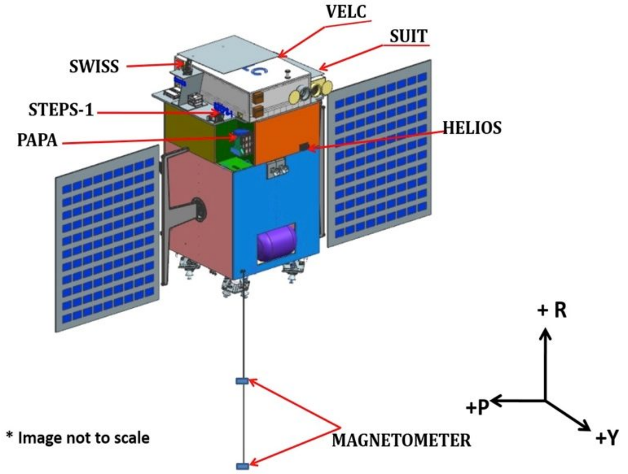

Figure 1: Illustrated model of the Aditya-L1 spacecraft showing the seven instruments (Image credit: ISRO)

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In this paper, we present the main science goals and the details of the SUIT instrument that is being developed by the Inter-University Centre for Astronomy and Astrophysics (IUCAA) in collaboration with the Indian Space Research Organization (ISRO). SUIT is an off-axis telescope designed to take images of the Sun in 11 distinct science filters in the near ultraviolet (NUV) region between 200-400 nm. SUIT will provide an unprecedented 24x7coverage of the Photosphere and the Chromosphere with low stray light and high contrast. Full disk images of the Sun have not been taken in this wavelength range from space. Therefore, SUIT will open up an unchartered window by providing opportunity to simultaneously study the solar atmospheric dynamics as well as measurements of spatially resolved solar spectral irradiance. It will address the following specific topics and associated questions:

1. Coupling and Energetics of the Solar Atmosphere: Which processes channel and transfer the energy from the Photosphere to the Chromosphere and partly into upper atmosphere?
2. Dynamics of the solar atmosphere: How are dynamic events, such as spicules, chromospheric jets, etc. initiated?
3. Prominence Studies: What are the mechanisms responsible for stability, dynamics and eruption of solar prominences?
4. Initiation of CMEs and Space Weather: What are the kinematics of erupting prominences during the early phase?
5. Sun-Climate studies: How relevant is the variability of solar UV irradiance for the Earth's climate?

The rest of the paper is structured as follows: In section 2, design requirements and system constraints are summarized. The sections 3 and 4 provide an overview of the instrument design and various design challenges that are being addressed.

Table 1: Science objectives of various instruments onboard the Aditya-L1 Mission

Instrument	Science objectives	Institute
Visible Emission Line Coronagraph (VELC)	• Plasma and magnetic field dynamics of solar corona • The dynamics and origins of Coronal Mass Ejections (CMEs)	Indian Institute of Astrophysics (IIA)
Solar Ultraviolet Imaging Telescope (SUIT)	• Dynamics of the solar atmosphere • UV irradiance variability of the spatially resolved Sun	Inter-University Centre for Astronomy and Astrophysics (IUCAA)
Aditya Solar wind Particle EXperiment (ASPEX)	• Spectral and spatial characteristics of Solar wind • Variability of Solar wind properties	Physical Research Laboratory (PRL)
Plasma Analyzer Package for Aditya (PAPA)	• Composition and Energy distribution of Solar wind	Space Physics Laboratory (SPL)
Solar Low Energy X-ray Spectrometer (SoLEXS)	• X-Ray Flare events • Heating mechanisms of Solar Corona	ISRO Satellite Centre (ISAC)
High Energy L1 Orbiting X-ray Spectrometer (HEL1OS)	• Monitoring dynamics events in of Solar Corona	SRO Satellite Centre (ISAC) and Udaipur Solar Observatory (USO-PRL)

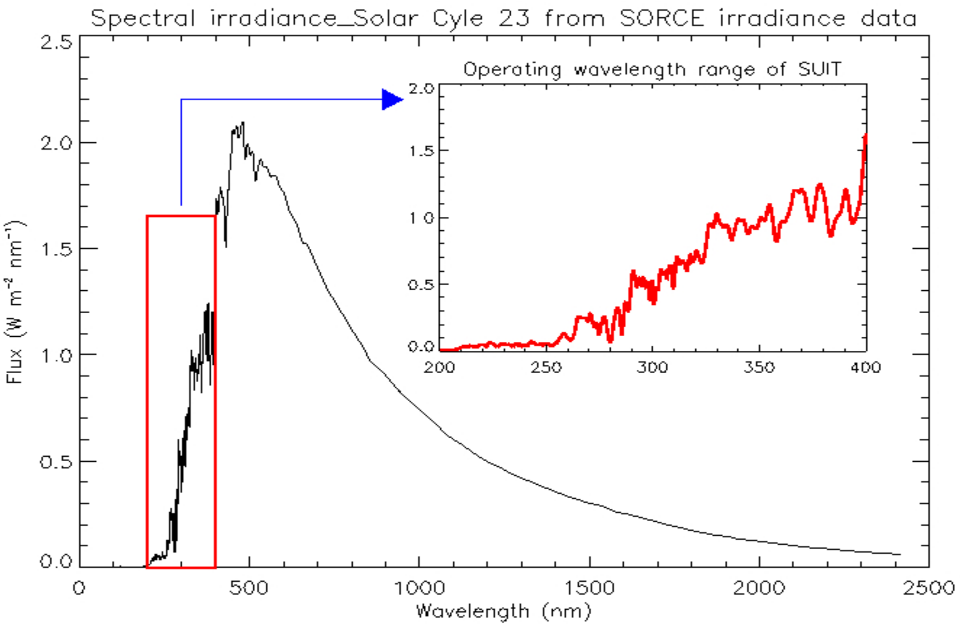

Figure 2: Solar spectral radiative flux at 1 AU with the inset showing the operating wavelength range for SUIT

2. DESIGN REQUIREMENTS AND SYSTEM CONSTRAINTS

The SUIT instrument design has to meet the science objectives discussed in the previous section, taking into consideration the mission timeline, spacecraft, operations and component-level constraints. In this section, we briefly discuss the requirements and system constraints that drive the design of the instrument.

2.1 Top Level Science Requirements

The instrument design and development is based on the top level requirements derived from the science objectives (Table 2). The 11 spectral channels with their scientific objectives, central wavelength and bandpass are given in Table 3.

Table 2: Top Level Science requirements for SUIT

TOP LEVEL SCIENCE REQUIREMENTS	
Spectral Coverage	200-400 nm
Spectral Channels	11 (3 Broadband & 8 Narrowband- see Table 3 for details)
Spatial Coverage	a) Full disk (up to ~1.2 Solar Radii): ~38 arcmin b) Partial field (~512x512 sq. arcsecond adaptable region of interest on solar disk)
Temporal coverage	Uninterrupted 24x7 coverage of: a) Full disk: every 30 mins in all 11 filters irrespective of modes of operation b) Partial field: every ~40 seconds in all 8 Narrowband filters
Angular resolution	1.4 arcsec on the Sun
Minimum Signal to Noise Ratio	100 in dark regions
Contrast	10:1 contrast between bright and dark features at 10’’ length scales
Scattered/Stray light	Combined scattering at 10” scales a) For Bright spots: Should be less than 0.11% of mean Solar flux b) For dark spots, it is 0.036% of mean Solar flux

Table 3: SUIT spectral channels and their Science Description

Spectral Channels (nm)	Bandpass (nm)	Science
214	5	Dynamics of the Magnetic bright points in the photosphere
274.7, Blue wing of Mg lines	0.4	Chromospheric and lower transition region dynamics, waves, shocks, filaments, and prominences; Sun-Earth Climate connection
279.6, Mg II h line	0.4	
280.3 Mg II k line	0.4	
283.2, Red wing of the Mg II lines	0.4	
300	1	Sunspot complexity; Dynamics
388	1	Lower Photosphere, monitoring magnetic flux proxies
397.8	0.1	Ca II line, Chromosphere
200-242, O_2 Herzberg Continuum, O_3 Hartley Band	42	Sun-Earth Climate Connection: Ozone balance in stratosphere
242-300, O_3 Hartley Band	58	
320-360, O_3 Huggins Bands	40	

2.2 System Constraints

The system constraints on the SUIT design were identified based on mission parameters, spacecraft (S/C) level mass, power budgets, design standards, bus configuration and availability of components. Some of the critical constraints are listed in Table 4.

Table 4: Critical system constraints for SUIT

Critical Design Constraints for the SUIT	
Mass budget	<35 Kg
Power budget	<33 W
Volume of the optical bench on S/C	~1100x350x280 mm
Volume for the electronics box on S/C	~250x200x200 mm
Launch	In 2019-20 timeframe
Orbit	Halo Orbit around L1
Pointing capabilities	Pointing up to 90° away from Sun for calibration
Availability of critical components	Space qualified detector for Qualification and Flight models in the mission timeframe

The most crucial constraint is the delivery timeline for a proposed launch in the 2019-2020 timeframe, which requires the instrument to be delivered by 2018-2019. The development and delivery of a CCD in this timeframe is a big challenge, and hence, the detector selection and procurement is a major driver in the instrument design and development process.

2.3 Instrument top-level functional and performance requirements

Table 5 depicts the top-level functional and performance requirements for the instrument design that were derived from science requirements and systems constraints (discussed in section 2.1 and 2.2, respectively). These requirements are the drivers for the instrument optical design, analysis and validation.

Table 5: Instrument functional and performance requirements

Spectral Coverage	200-400 nm
Field of view	~0.8 degrees of arc (Field extending up to ~1.6 Solar Radius)
Image Quality - Angular Resolution	1.4 arcseconds
Image Quality- Contrast	MTF at 42 l/mm should be greater than 10 %
Primary aperture	140.8 mm ($2.44\lambda/\Delta\theta$, @280nm *for* $\Delta\theta = 1$ arcsecond)
Effective Focal Length	3500 mm (pixel size/angular coverage per pixel)
Image Size	4kx4k (Detector)

3. INSTRUMENT DESIGN OVERVIEW

The instrument's present design was achieved after several iterations and design trade-offs that are beyond the scope of this paper. In this section, we provide an overview of the current status of the instrument design and discuss the various subsystems and critical components.

3.1 Instrument functional description

SUIT has two main sub-units: the optical bench and the electronics box. The optical bench has a two mirror off-axis telescope designed and optimized to take high-resolution images in the 200-400 nm region with a passively cooled CCD detector. The optical bench consists of the mirrors, focal plane assembly, filter wheel, shutter & focusing mechanisms, baffles, aperture filter, enclosure covers and structural support elements. The optical bench will be mounted on the top deck of the spacecraft along with some of the other instruments. Figure 3 depicts the functional layout of the optical bench and the electronics box along with various components.

There are total 11 science filters (8 Narrow-band and 3 Broadband) that will be mounted on two filter wheels each with 8 filter slots (a total of 16 slots). The 5 other slots will have 1 clear glass filter, 3 neutral density filters and 1 closed position for taking dark frames. The filter wheels will be driven by two independent drives that will bring a predefined combination of neutral density filter and science filter into the beam path. The exposure control is done using a diaphragm shutter that is located in front of the first filter wheel. Depending on the combination of the science filters chosen, the exposure time can vary between few tens to a few hundred milliseconds.

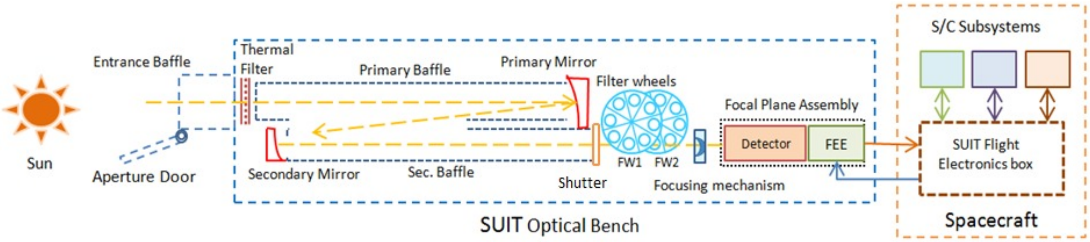

Figure 3: Functional Diagram of SUIT

The SUIT instrument will take images of the Sun 24x7 throughout its operational life, except for the in-orbit calibration (initial and periodic) phases of the instrument and the periodic orbit correction maneuvers for the spacecraft. The entrance aperture is proposed to have a multi-operation door mechanism that can be opened and closed during the calibration and orbit maneuvers.

The electronics box consists of all the processing and control electronics for the detector and the mechanisms of SUIT. This box will be mounted inside the S/C bus below the top deck. The electronics have been separated from the optical bench to minimize the contamination of optics due to molecular outgassing. The front-end electronics located in the vicinity of the CCD will be interfaced with the readout electronics through interface cables for data and power. After the exposure, the shutter will remain closed while the detector is read and the filter wheels are moved into the position for the next exposure.

The aim is to provide a high-degree of autonomy to the system to operate 24x7 with minimum interventions from the ground operations team. Nevertheless, there are provisions in the design to override sequences on the onboard computers by ground commands. This will provide flexibility for operating the instrument in different operations modes as per the requirement of the science team.

3.2 Optical design

The optical design of SUIT was done based on the instrument functional performance requirements and the design constraints. The two-mirror off-axis configuration was selected to minimize the scattering effects. It also prevents any direct straylight from the telescope entrance from reaching the focal plane. The use of aspheric surfaces for the mirrors reduces the number of components to correct for abberation all over the field of view and only a single element field corrector lens is used just before the image plane.

The final design configuration of SUIT has a primary mirror with a clear aperture (CA) of 141mm, which is sufficient to give diffraction limited images of 1 arcsec diameter at 280nm wavelength. The SUIT image plane uses a 4096×4096 CCD sensor with 12 micron square pixels and offers a pixel sampling of 0.7 arcseconds; providing a minimum angular resolution of ~1.4 arcseconds.

The focal length of the system is 3500mm with a field of view of approximately 0.8° (up to ~1.6 Solar Radius); covering the entire solar disk and leaving sufficient margin for potential misalignments between the optical axes of SUIT and VELC. The field correcting lens produces uniform image quality throughout the field of view with an acceptable dispersion due to wideband filters. It also allows to compensate for image focus shift due to any possible change in the thermal configuration of the instrument. The 2D layout of the optical design for SUIT is shown in Figure 4.

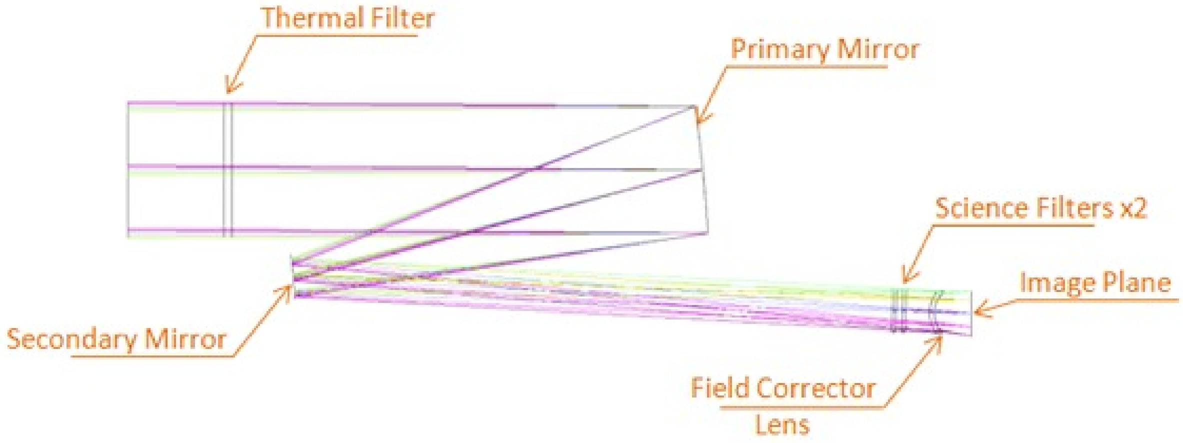

Figure 4: 2D layout of the SUIT Optical design

3.3 Detector

Considering the cost and availability of space qualified detectors within the stringent schedule, the baseline for the SUIT detector is to use an existing space qualified CCD detector that has been developed by E2V. The device under consideration for SUIT is e2v CCD 272-84, a 4096 x 4906 back-illuminated detector with 12 micron pixel size. This device is similar to CCD 203-82 that was used in the Atmospheric Imaging Assembly (AIA) and Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory.[2,3]

For SUIT, the CCD 272-84 will be optimized with anti-reflection coating to minimize ghosting through multiple reflections from the focusing lens and/or filters in the UV 200-400 nm region. The baseline specifications for the detector are summarized in Table 6.

Table 6: Baseline specification for SUIT detector

Image Area	49.2 mm x 49.2 mm
Format	4096x4096
Pixel size	12 μm x 12 μm
No. of Output amplifiers	4
Full Well Capacity (Typical)	175,000/pix
Mean Dark current at -40˚C (Typical)	35 e^-/pix/s
Read out noise at 250 kilohertz	~4 e^- rms
Nominal operational temperature	-40˚C
Quantum Efficiency	Min. 25% at 200 nm
Outgassing	Total Mass Loss (TML) ≤0.1% and Collected Volatile Condensable Material ≤0.1%
Radiation Hardness	End of Life Total ionization dose: 10 krad (Si) direct exposure from a radiation source at 2 krads/hour. Displacement Damage Equivalent Fluence: $1x10^{10}$ cm^{-2}

3.4 Mechanical Systems

All the opto-mechanical and electronic systems of SUIT, including mirrors, filters, baffles, mechanisms and focal plane assembly, will be mounted on a light-weighted optical bench made of Titanium alloy. The optical bench would be covered with an enclosure that will provide protection from external environment, straylight and contamination. The optical bench will be mounted on the spacecraft top deck with six mounting legs.

The control systems for the instrument and the detector readout electronics will be housed separately in a electronics box mounted inside the spacecraft below the top deck. The data, control and power cables from the mechanisms and the focal plane assembly will be relayed to the electronics box.

The mechanical system of SUIT, shown in Figure 5, includes:

1. Optical bench on which the opto-mechanical and electronic systems will be mounted.
2. Opto-mechanical/optoelectronics assemblies and mechanisms including:
    - Primary Mirror assembly,
    - Secondary Mirror assembly,
    - Thermal Filter assembly,
    - Two filter wheel mechanisms,
    - Focal plane assembly,
    - Shutter mechanism,
    - Focusing mechanisms
    - Door mechanism
3. Scattered light reduction baffles:
    - Primary, secondary baffle mounted inside the enclosure
    - External baffle is mounted on the front panel of the enclosure. The entrance door mechanism is attached on the external baffle with structural elements.
4. Enclosure made of honeycomb panels and covered with multilayer insulation
5. Thermal control system
    - Heaters and thermal insulation for optical bench and enclosure
    - Cold finger and radiator plates for passive cooling of detector

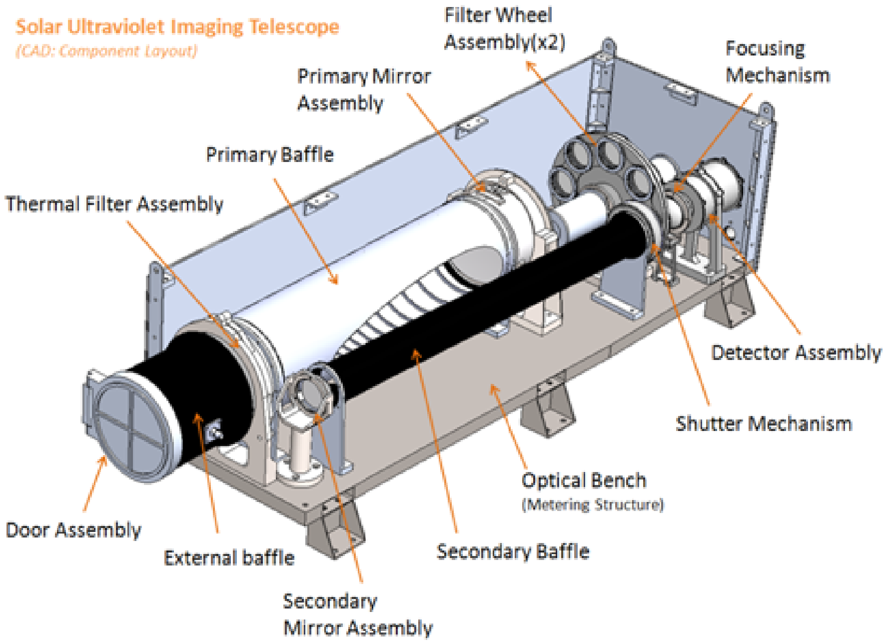

Figure 5: SUIT components internal layout (front, right and top covers removed)

3.5 Thermal control

The thermal environment at L1 is more stable compared to Low-earth orbits where the satellite has to go through periodic phases of eclipses. Thus, a very stable thermal equilibrium can be achieved at the spacecraft and the instrument level; except for the seasonal changes due to the elliptical orbit of the earth, variation in heat dissipation from active components like motors and the long term in-orbit degradation of thermal control elements.

The temperature of the optical cavity will be maintained in the operational range of 20 +/-3 ^{0}C by heaters and Multi-Layer Insulation (MLI) blankets that will cover the entire instrument. The thermal performance will be monitored using temperature sensors attached on the optical bench.

As the thermal filer rejects most of the solar flux, the heat load on the Primary and Secondary Mirrors is very low and no cooling would be required for these elements. However, the detector will have to be operated at -40 +/1 ^{0}C to minimize the dark current. As the instrument has a limited power budget, an active cooling system cannot be used. Therefore, the focal plane will be cooled using a passive cooling system; with radiator plates and heat pipes connected to the detector by a cold finger.

4. DESIGN CHALLENGES

There are various design challenges that need to be addressed in order to achieve the functional capabilities required to meet the science requirements. In this section, we briefly discuss these challenges and the design strategies adopted to address them.

4.1 Thermal control and flux management

In the 200-400 nm region solar flux varies by a factor of 20 as shown in the insert in Figure 2. Also, a contrast of up to 10:1 may exist between nearby bright and dark features on the solar disk in different filters. The challenge here is to manage the flux to prevent the heating of the optics and the detector, but still be able to achieve a signal to noise ratio of 100 in the dark regions (see section 2.1).

The aperture rejects the solar flux in the visible and infrared region and only allows a fraction of the in-band flux (between 200-400 nm) to pass through. It is to prevent overheating of the optics and saturation of the detector by the excessive in-band and out of band (above 200nm and below 400 nm) flux coming from the Sun. Furthermore, the science filters are combined with neutral density filters to prevent the saturation of the detector and meet the signal to noise requirement (see section 2.1).

4.2 Data volume and compression

The total data volume generated by SUIT per day will be approximately 37 GB. However, due to limited visibility of the satellite (downlink window of ~8 hours per day) and available bandwidth (~4Mbits/s), the total downlink budget for SUIT is ~8 GB over a 24 hour period. Therefore, SUIT data must be compressed onboard by a factor of 5 before the downlink.

With lossless techniques the compression achieved is around 2 for simulated data. Therefore, feasibility of a combination of two data compression algorithms – a lossy compression (square-root[4]) followed by a modified loss-less compression (variable-bit Rice[5]) is being investigated. In the square-root compression, pixels having a DN (Data Number) less than a threshold value are not altered but pixels having higher than threshold values are replaced by taking square-roots of the respective DN. In the variable-bit Rice compression, every pixel DN is coded in a different length-word with a prior knowledge of the bit-lengths. A combination of these two techniques a compression factor of 2.8 has been achieved.

Other compression techniques such as JPEG are being investigated to achieve the high compression factor required for SUIT.

4.3 Scattered and Stray light reduction

The sensitivity of the instrument is strongly affected by the light scattered from different sources:

1. Micro-roughness of the optical surfaces can cause large angle scatter in the observing band.
2. Particulate contaminants on critical surfaces can scatter light onto the detector.
3. Low-spatial frequency deformation (figure errors) of the optical surfaces can cause broadening of PSF wings.

As discussed in section 2.1, the contrast between the bright and dark features on the solar disk is not expected to be more than 10:1 (at 10 arcseconds lengths scales). This requires the instrument scattered light into the dark regions (in the image) to be within 0.036% of mean Solar flux (for target SNR of 100) and into the bright regions within 0.11 % of the mean Solar flux.

The following design provisions are made to limit the scattered and straylight:

a) Baffles with vanes: The Primary, secondary and external baffles block any straylight from directly reaching the detector. These baffles will have internal vanes and will be black painted with Aeroglaze z306 to suppress any first and higher order scattered light to reach the critical surfaces.[6,7] Other mechanical surfaces in the optical cavity will also be painted with Aeroglaze z306 to prevent any scattering effects.

b) The secondary mirror followed by the primary mirror is a major contributor to scattered light (based on scattering analysis of SUIT optical train with baffles in ASAP^{TM}) and they will be finished to a surface roughness of 7 Å or better. K-correlation Bidirectional Scattering Distribution Function (BSDF) model was used to study the scatter from optical rough surfaces.[10,11] The model parameters were estimated through fitting experimental Power Spectral Density (PSD) data on a polished test surface with K-correlation form.

c) The scatter contribution due to particulate contamination of optical surfaces was estimated by Mie scattering simulation in ASAP^{TM}. The levels of particulate contamination in the optical cavity will be minimized by a firm contamination mitigation and control strategy discussed briefly in the next section.

4.4 Contamination Control

Contamination control and cleanliness is a critical area of concern for SUIT as it operates in the UV region. Both molecular and particulate contaminants on any critical surfaces in the light path significantly degrade the performance of the instrument.[12,13]

In order to mitigate the impact of contamination, the Assembly, Integration and Testing (AIT) of SUIT will be done in a Class 100 environment. The optical cavity will be purged with ultra-clean Nitrogen after the initial assembly. Additionally, the components and instrument will be transported in purged bags and containers to protect them from external environment.

Contamination mitigation and control practices such as screening and selection of materials, vacuum bake-out, ultrasonic cleaning and/or solvent cleaning at component level, carefully designed handling and cleaning schedules, continuous and periodic monitoring of contamination levels on critical components and strictly controlled clean areas with trained personnel for AIT activities.

5. FUTURE WORK

The evolution of the design of SUIT and development progress was discussed in this paper including the provisions for handling major design challenges. During the development process several questions and challenges must be addressed to meet the mission timeline and achieve the scientific objectives of the instrument. The following aspects have been recognized as key areas where future work is required during the design and development process:

- Optical design: Ghost image analysis, on-board and ground based calibration procedures
- Detailed design: Mechanical system, Thermal control system, Control electronics and flight software
- Development and Qualification: Aperture filter, shutter mechanism and focusing mechanism
- Development of data pipelines for distribution of science data to end-users
- Development and Testing of integrated qualification and flight models

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