

Design and development up to TRL 6 of a Sun polychromator for the TRUTHS mission

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ABSTRACT

TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio-Studies) is a climate-focused Earth-observation mission intended to establish a reference baseline of the planet's radiative state, support climate-model improvement and forecast validation, accelerate detection of climate-change and mitigation effects, and improve consistency across the global Earth-observation system.

The Solar Polychromator (SPC) is a key element of the TRUTHS On-Board Calibration System (OBCS). It provides a solar-disc image over a selectable spectral range tunable across 320-2400 nm, enabling high-accuracy radiometric calibration of the TRUTHS radiometer and spectrometer. The SPC combines a three-prism dispersive assembly, reflective imaging optics, an actuated wavelength-selection mirror, and a hexagonal homogenizer. The homogenizer reduces the transfer of input pointing variations into the downstream pupil distribution, improving output-power and PSRF stability. Spectral filtering is produced by the wavelength-dependent displacement and vignetting of solar-disc images at the output port.

This work presents optical design, radiometric performance, straylight and self-emission analyses, and structural-thermal-optical performance assessment, including micro-vibration effects. A dispersive-element breadboard was characterized using monochromator illumination. Measurements of the filtering response and straylight at representative wavelengths validated the optical concept. The measured PSRFs reproduced the predicted curve shapes, while the straylight measurements confirmed the predicted spectral trend and order of magnitude.

Keywords: TRUTHS, Solar Polychromator, optical design, PSRF, spectral filtering, straylight, STOP analysis, breadboard validation

1 INTRODUCTION

TRUTHS is intended to establish a benchmark measurement of the radiative state of the Earth, enabling future observations to be compared against a stable and SI-traceable reference^[1]. The mission supports improved climate-model evaluation, earlier detection of climate trends, and enhanced consistency across the global Earth-observation system. The payload combines a Hyperspectral Imaging Spectrometer, a Cryogenic Solar Absolute Radiometer, and an On-Board Calibration System that transfers the radiometric reference to the imaging instrument.

The SPC receives broadband solar radiation and provides a spectrally filtered output beam with a selectable central wavelength across 320-2400 nm. Its optical performance is characterized by the Power Spectral Response Function (PSRF), peak wavelength and full width at half maximum (FWHM), spectral output power, integrated power stability, and spectral straylight. These quantities are tightly coupled as filtering is generated by spatial separation and vignetting of wavelength-dependent solar images.

This paper presents the SPC optical concept and its verification through nominal radiometric analysis, alignment and pointing assessment, coupled Structural-Thermal-Optical Performance (STOP) analysis, straylight and self-emission analysis, and breadboard correlation. The analyses use an extended-source model so that dispersion, image distortion, limb darkening, pupil illumination, and output-port vignetting are treated consistently.

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2 OPTICAL DESIGN

The optical design provides tunable spectral filtering over the complete operating range while maintaining the required response, throughput, and stability. Sequential Zemax OpticStudio® and non-sequential FRED® models were used to assess nominal and perturbed optical performance and unwanted radiation, respectively. Both models used consistent source, geometry, transmission, and aperture definitions. The optical models were coupled with the opto-mechanical structural and thermal analyses to evaluate performance under operational environmental conditions.^[3]

2.1 Functional principle and architecture

An entrance folding mirror (FM1) directs the solar beam into the optical-bench plane. A first off-axis paraboloid (M1) images the solar disc onto the homogenizer (Homog), which acts as the field stop, while a second off-axis paraboloid (M2) recollimates the beam towards the three-prism assembly (P1, P2, P3). The wavelength-selection mechanism (WSM), which includes an actuated flat mirror and a single-degree-of-freedom rotation mechanism derived from one scan axis of the Meteosat Third Generation Scan Assembly (MTG-SCA)^[4], directs the selected dispersed beam through the aperture stop (ApStop). A third off-axis paraboloid (M3) then focuses the selected solar image onto the output port (OP), which acts as a spatial spectral filter. For a fixed WSM position, the image at the selected wavelength is centered on the OP, while neighboring wavelengths are progressively displaced and vignetted. The resulting PSRF is governed by the solar angular diameter and limb-darkening distribution, the spectral separation and image distortion introduced by the prism assembly, the scale of the solar image at the output port, the port geometry, and the pupil-illumination distribution.

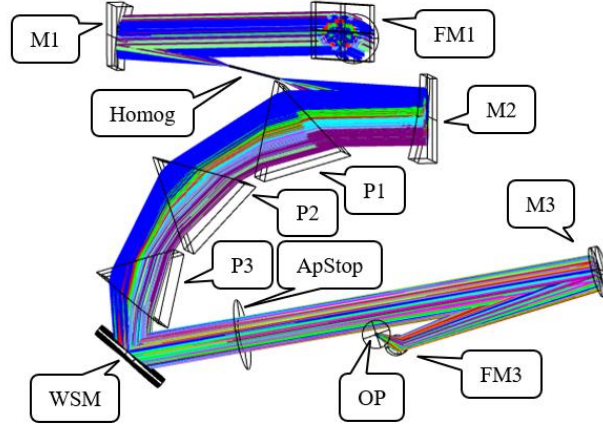


Figure 1. Optical configuration of the SPC showing the main diaphragms, mirrors, prisms, homogenizer, and WSM.

2.2 Extended solar source and limb-darkening model

The Sun is represented as an extended source whose apparent angular diameter defines the entrance field. Its disc radiance is weighed using a wavelength-dependent limb-darkening model.^[5] The relative radiance is represented by the wavelength-dependent polynomial used in the source model, where u, v, w are the tabulated limb-darkening coefficients for each wavelength and μ the direction cosine relative to local solar normal obtained from the normalized radial coordinate ρ :

$$\mu = \cos(\gamma) = \sqrt{1 - \rho^2} \quad (1)$$

$$I(\mu, \lambda) = u + (1 - u)\mu + v \mu \ln\left(\frac{2\mu}{\mu+1}\right) + w \mu \left(\mu \ln\left(\frac{\mu+1}{\mu}\right) - \ln 2\right) \quad (2)$$

The wavelength-dependent coefficients were applied to field points distributed across the solar disc, and the resulting radiance distribution was normalized to the adopted solar spectral irradiance at each wavelength. Limb darkening affects the PSRF because the OP clips the low-radiance solar-disc edge before reaching the brighter central region.

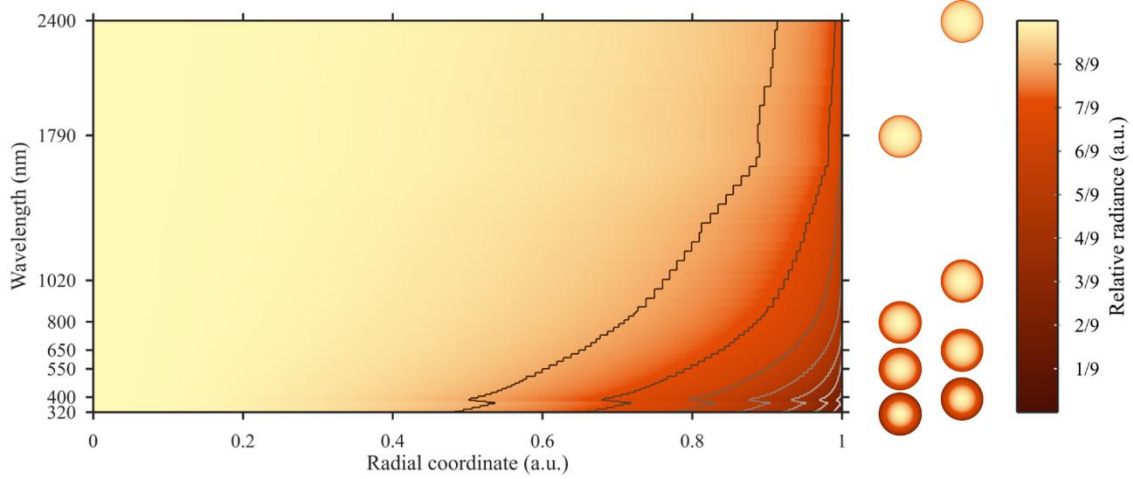


Figure 2. Solar limb-darkening profiles used in the extended-source model, with contour lines representing the wavelength-dependent relative-radiance levels assigned across the solar disc.

2.3 Homogenizer and filtering stability

Satellite pointing variations displace the solar image at the homogenizer entrance and would modify the illumination of the dispersive assembly and OP without the homogenizer. The hexagonal light pipe reduces this sensitivity through multiple total internal reflections, which redistribute the input beam into overlapping spatial and angular components. To maximize scrambling performance, the homogenizer was designed with the longest feasible rod and a cross-section approaching circular symmetry, while accommodating mechanical constraints; a regular hexagon was selected as the most practical implementation. The near-field power distribution defines the spatial weighting propagated toward the OP, while the far-field distribution determines the illumination of the ApStop, which changes with wavelength because of the dispersive assembly. Stable filtering requires both distributions to remain aligned with the downstream optical apertures.

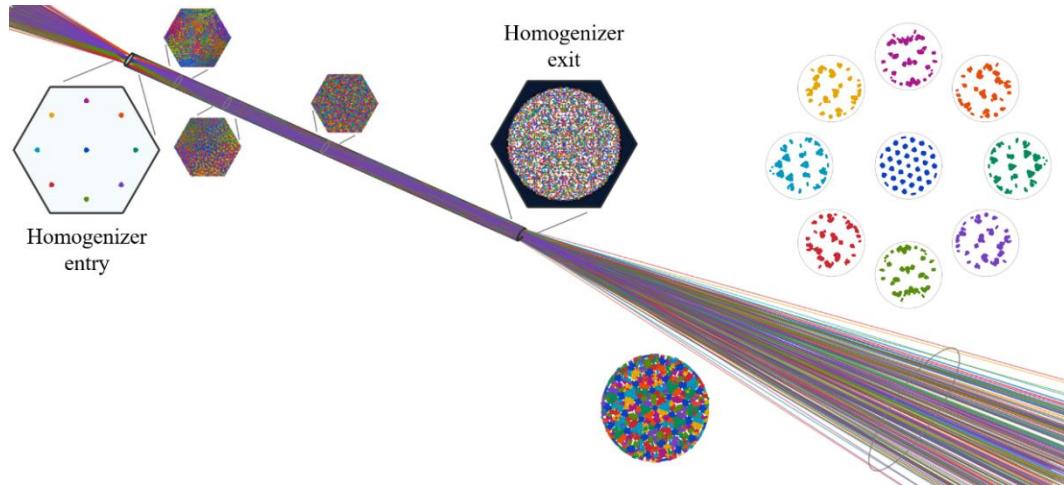


Figure 3. Homogenizer operating principle, showing the near-field spatial distribution and far-field angular distribution to stabilize the filtering curve and power output respectively.

The characteristic ApStop pattern, including the number, spacing, orientation, and clipping of the replicated components, was used to confirm homogenizer alignment and identify pupil losses.

2.4 Dispersive-element trade-off and design

A prism assembly and a diffraction grating were compared in terms of broadband dispersion, throughput, diffraction-order management, straylight, thermo-optic stability, manufacturability, and accommodation. The grating solution provided compact dispersion but required order-sorting functions and introduced wavelength-dependent efficiency and polarization effects. The prism solution avoided order overlap and allowed higher broadband throughput, at the cost of nonlinear dispersion, increased optical path length, and wavelength-dependent image distortion. The triangular prism architecture was selected as the lower-risk solution for the required radiometric performance.

The dispersive assembly contains three fused-silica prisms. Fused silica provides suitable broadband transmission and compatibility with the required environmental conditions, although bulk absorption becomes increasingly relevant toward the long-wavelength boundary. Prism orientations were established from chief-ray deviation at representative wavelengths and refined using the extended-source model. Clear apertures and footprints were evaluated over the complete wavelength-selection scan. The model included material dispersion, bulk transmission, interface losses, and AR coating performance.

2.5 Minimum-deviation reference and image distortion

The prism train operates at minimum deviation angle for a reference wavelength near the short-wavelength limit. Under this condition, incidence and emergence angles are equal and the ray path is symmetric, minimizing solar-image distortion in the dispersion direction. Away from the reference, wavelength-dependent refraction produces Littrow-type image expansion or compression. For each prism, the scale factor depends on the beam incidence angle at the two prism faces:

$$r \propto \cos(\theta_{out}) / \cos(\theta_{in}) \quad (3)$$

The effect accumulates across the three prisms. Image distortion consequently increases with spectral distance from the reference wavelength and changes the overlap between the solar image and the OP which itself decreases with spectral distance from the pointing wavelength. Both wavelength-dependent effects combine to shape the PSRF.

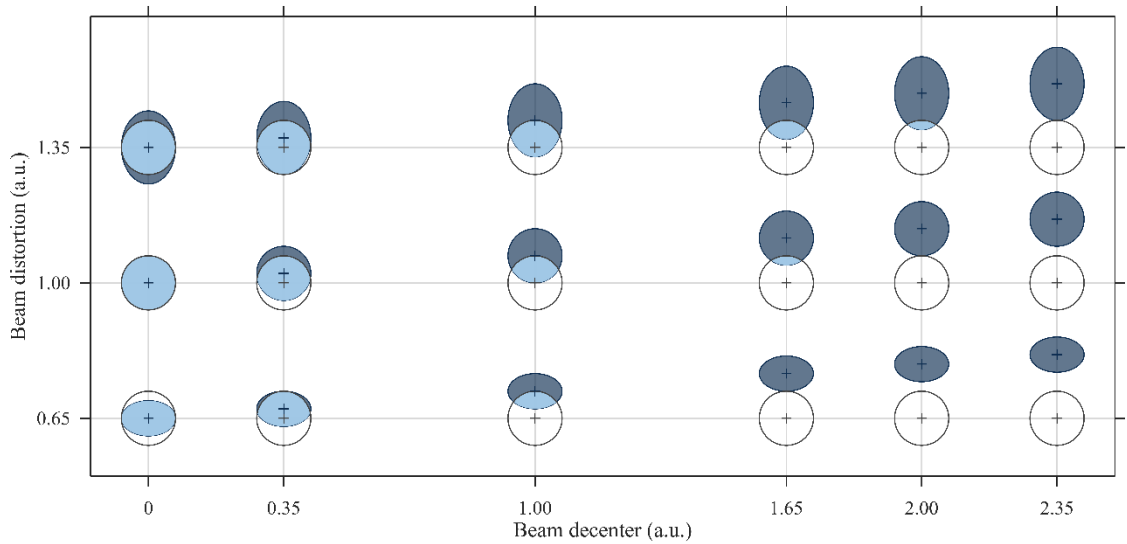


Figure 4. Predicted Littrow-type image distortion within the prism assembly, illustrating wavelength-dependent decenter and expansion or compression of the solar image relative to the OP and related changes in vignetting.

This effect, together with nonlinear dispersion and limb darkening, explains the wavelength-dependent PSRF width, asymmetry, and flattening.

2.6 Tolerancing and sensitivity analysis

Alignment and manufacturing tolerances were assessed through their effects on PSRF peak position, FWHM, power output, and curve shape. Dispersive-element alignment primarily affected spectral position and bandwidth, whereas homogenizer alignment and transverse pupil displacement mainly affected ray weighting and throughput. The long, wavelength-dependent optical path through the prism assembly produced significant transverse pupil displacement, making it a key factor in pupil alignment, vignetting, and throughput variation.

The optical model was coupled with the opto-mechanical structural and thermal analyses to evaluate thermo-elastic displacement, thermo-optic effects, and micro-vibration. Thermo-optic and thermo-elastic contributions were evaluated separately to distinguish spectral displacement from pupil redistribution. Micro-vibration and photo-elastic effects were found to be non-driving contributors over the relevant measurement interval, as the associated fluctuations were averaged out by the integration time of the power measurements.

3 OPTICAL PERFORMANCE ANALYSIS

Optical performance was evaluated across the complete operating range using the extended-source sequential model. The analysis included the PSRF, spectral and integrated output power, and sensitivity to pointing, alignment, structural, and thermal perturbations. All performance metrics were extracted using consistent source sampling, optical transmission, and wavelength grids.

3.1 Power Spectral Response Function

The PSRF describes the transmitted output power as a function of wavelength for a fixed wavelength-selection mirror position. The FWHM is conventionally defined as the wavelength interval between the two half-maximum crossings:

$$\text{FWHM} = \lambda_{+50\%} - \lambda_{-50\%}. \quad (4)$$

An alternative definition was also evaluated to better account for irregular curve shapes:

$$\text{FWHM} = \int \frac{P_{out}(\lambda)}{P_{out}(\lambda_{peak})} d\lambda \quad (5)$$

Both definitions produced comparable results, although the integral definition better represented deformation near the PSRF edges.

For each selected central wavelength, a local spectral sweep was performed at a fixed WSM position. The peak wavelength, FWHM, integrated useful power, and low-level spectral wings were extracted from the resulting PSRF. The complete curve was used because FWHM alone does not describe asymmetry, flattening, or the spectral wings relevant to straylight assessment.

The wavelength dependence of the PSRF results from the combined effects of prism dispersion, wavelength-dependent absorption, enhanced by the long optical path length through the prism assembly, as well as geometrical effects associated with image distortion, output imaging, port geometry and pupil illumination.

High angular dispersion produces a narrow response near the short-wavelength end, whereas reduced dispersion and image compression broaden and flatten the response at longer wavelengths as can be observed in the simulated curves.

The same calculation was applied to nominal and perturbed configurations using a common spectral grid. The homogenizer reduced pointing-induced changes in the PSRF by stabilizing the downstream pupil illumination. The remaining differences were associated with pupil clipping, off-axis aberrations, and relative optical displacement. The analysis was also applied to the STOP cases derived from the coupled thermo-mechanical model, including thermo-elastic and thermo-optic effects. Performance remained stable for the combined pointing and STOP cases in hot and cold scenarios across the complete operating range. Even if not critical for operation the full orbit case presented bigger variations.

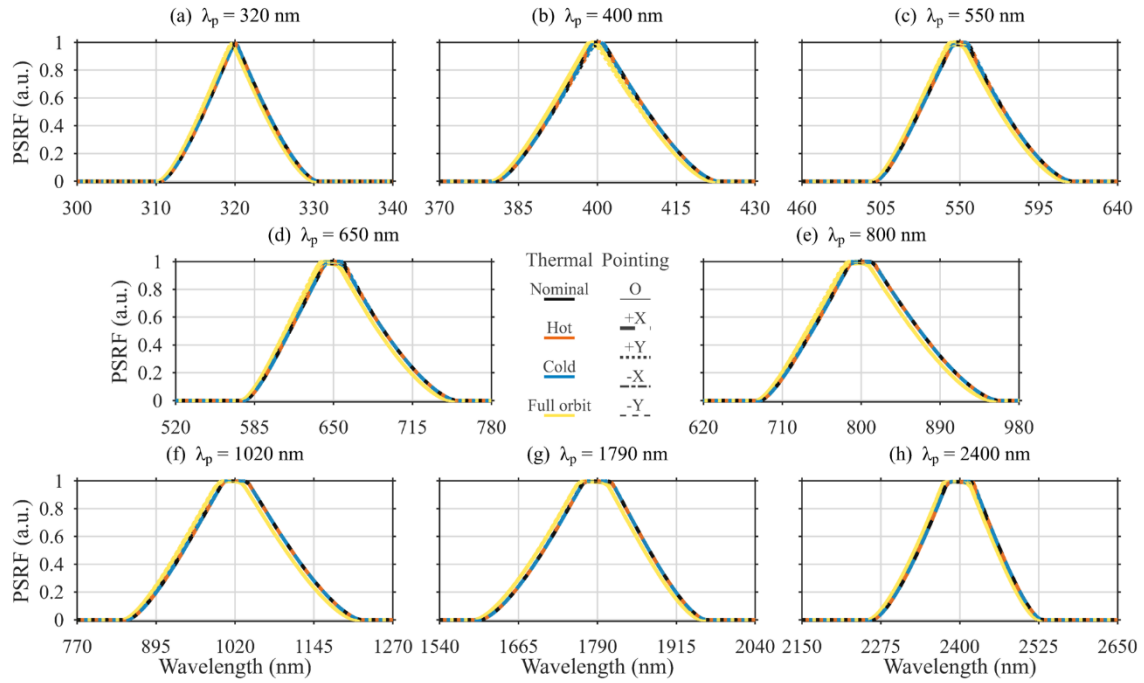


Figure 5. Comparison of representative PSRFs for the nominal configuration and the evaluated combined pointing, thermo-elastic, and thermo-optic cases.

3.2 Spectral output power

Spectral output power describes the wavelength-dependent PSRF peak power. It accounts for the solar spectral irradiance, wavelength-dependent optical transmission, prism absorption, coating performance, homogenizer losses, and vignetting. The predicted spectral output power was highest in the central operating region and decreased toward both spectral limits where the power values are critical.

3.3 Integrated output power

Integrated output power was calculated over the useful PSRF interval. Its variation across the operating range resulted from solar irradiance, optical transmission, PSRF width, image distortion, and output-port vignetting. These effects produced a significant dynamic range, with maximum power near the central spectral region and reduced power at the range boundaries. Because PSRF width varies with central wavelength, integrated power does not directly follow peak spectral output. Broader responses can partially compensate for reduced spectral power, while image distortion and vignetting can limit the increase in transmitted energy.

3.4 Output-power stability

The homogenizer introduced transmission losses through geometrical redistribution and downstream clipping. However, it improved output-power stability by reducing the sensitivity of downstream pupil illumination to input-pointing variations. Pointing-related stability was assessed by comparing the spectral and integrated output power obtained for nominal and perturbed solar fields at a fixed wavelength-selection mirror position. Radiometric stability was evaluated from the corresponding variation in spectral gain and integrated output. Residual changes were associated with pupil clipping, off-axis aberrations, and wavelength-dependent propagation through the dispersive assembly.

4 STRAYLIGHT AND SELF-EMISSION ANALYSIS

The non-sequential analysis quantified unwanted radiation at the OP and supported baffle design. Contributors were evaluated separately before consolidation to preserve their spectral signatures and relative importance.

4.1 Straylight model and contributors

Forward tracing identified paths from the solar input to the output, while backward tracing identified surfaces with direct or scattered visibility from the OP. The model included optical micro-roughness, particulate contamination, scratches and digs, diffuse mechanical reflection, and thermal self-emission. Spectral curves and integrated values were evaluated together to distinguish physical features from numerical ray-tracing noise and nominal PSRF wings.

Micro-roughness was represented with Harvey-type bidirectional scattering distribution function (BSDF) models, and contamination with Mie scattering and the allocated particle distribution. Straylight from surface imperfections was modeled as the combination of Lambertian scattering by the defect and diffraction around it. Contamination was the largest scattering contributor in several cases, while smooth-surface scatter remained well below its allocation.

The scatter analysis used a common detector normalization for all contributors. Each calculation retained the useful specular response together with the scattered component, allowing the integrated straylight ratio to be computed without combining results from differently normalized simulations. Isolated contributor runs were used for diagnosis, while the consolidated configuration was used for compliance assessment.

The wavelength grid was refined around the boundary of the useful PSRF region because this is where nominal response wings and scattered light overlap. At the longest-wavelength configurations, the fixed FWHM-based boundary included part of the distorted nominal response. These cases were identified separately and were not interpreted as pure scatter without additional curve-shape assessment.

4.2 Baffling and self-emission

Baffles were sized from the useful-ray envelope with an additional alignment margin and checked over the complete scan to avoid wavelength-dependent clipping. The selected configuration suppresses direct illumination of the ApStop surroundings and limits higher-order coupling from the prism region.

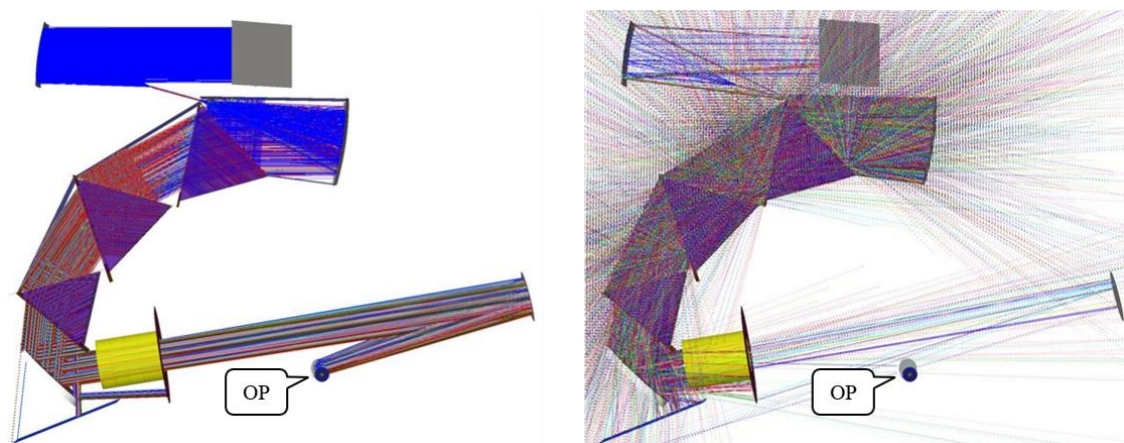


Figure 6. Non-sequential model showing the baffling strategy used to suppress straylight paths reaching the OP.

Absorbing structures were modeled as Lambertian emitters, with spectral radiance calculated using Planck's law at the applicable temperatures. Self-emission was negligible through most of the range but became relevant near the upper spectral boundary. The consolidated analysis remained below the in-band requirement, although the lowest-level long-wavelength cases require refined spectral sampling and ray-tracing convergence.

5 BREADBOARD VALIDATION AND MODEL CORRELATION

A dispersive-element breadboard was developed to validate the principal spectral-filtering functions and correlate the optical models. This section presents the test configuration, homogenizer alignment, PSRF measurements, and straylight correlation results.^[6]

5.1 Test configuration

The dispersive element breadboard (DE BB) reproduced the dispersive and filtering functions of the flight concept, while laboratory source and detector relays replaced the flight input and output interfaces. A monochromator and fiber relay provided the spectral input, configured to simulate the apparent size of the solar disc, and a reference configuration was used to correct the combined source, fiber, and detector response. The wavelength-selection relationship was verified independently before the complete PSRF was measured.

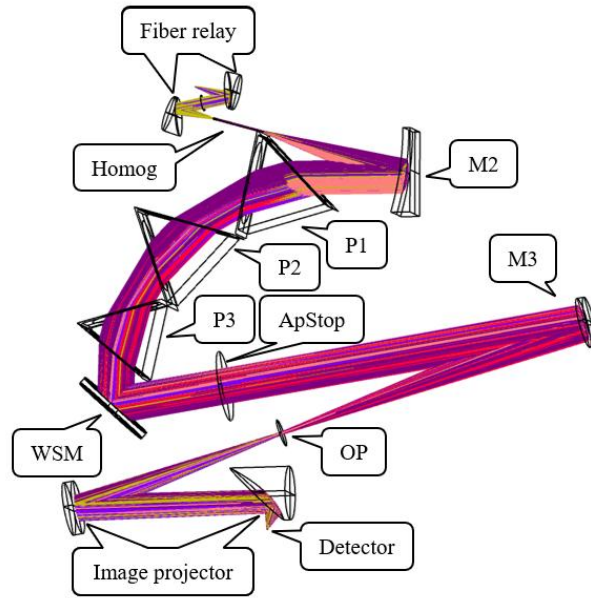


Figure 7. Optical configuration of the DE BB used for PSRF characterization and correlation with the optical model.

5.2 PSRF correlation

The breadboard model was correlated progressively using measured source and hardware data. The source numerical aperture and irradiance distribution were updated first, followed by homogenizer alignment and output-port geometry. Coating and bulk-transmission data were introduced only after the geometrical response had been correlated, preventing radiometric adjustments from compensating for alignment errors. The output-port image constrained the image geometry, while the ApStop pattern constrained homogenizer alignment and pupil illumination.

Homogenizer alignment was confirmed by comparing the predicted and measured ApStop irradiance patterns. The arrangement and edge clipping of the replicated components provided a more sensitive criterion than maximizing output power alone. Once the expected pattern was reproduced, the measured PSRF showed substantially improved agreement with the optical model.

The correlated model reproduced the measured FWHM within 1.5-8.7%. The largest deviation occurred at 785 nm and slightly exceeded the original 7% correlation margin, which did not account for the identified homogenizer and test-equipment alignment effects. These effects should therefore be included in future tolerance and correlation assessments.

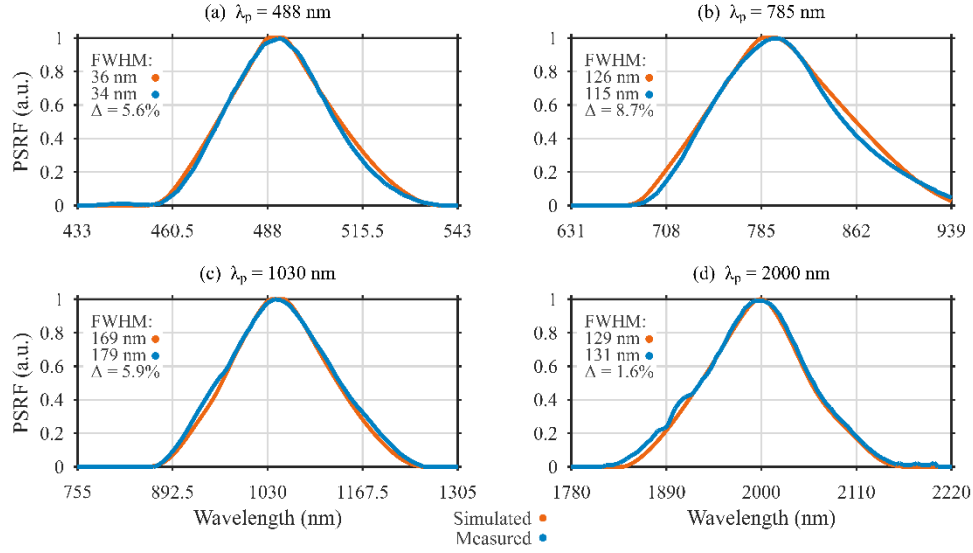


Figure 8. Comparison between measured and correlated PSRFs at four representative wavelengths confirming modeling of the experimental results.

The correlated PSRF curves also retain the expected wavelength-dependent flattening associated with the prism train. This behavior is consistent with the residual distortion predicted away from the minimum-deviation reference wavelength. The agreement of the measured and modeled curve shapes and FWHM confirms the representativeness of the model.

5.3 Straylight correlation

Measured and predicted straylight curves showed similar spectral trends and the same order of magnitude. The comparison was limited by detector's dark response, ambient-light leakage, large reference corrections in low-source-power regions, ray-tracing convergence, and the adopted PSRF boundary definition of 2.2 FWHM, with signal within this range attributed to the PSRF rather than straylight.

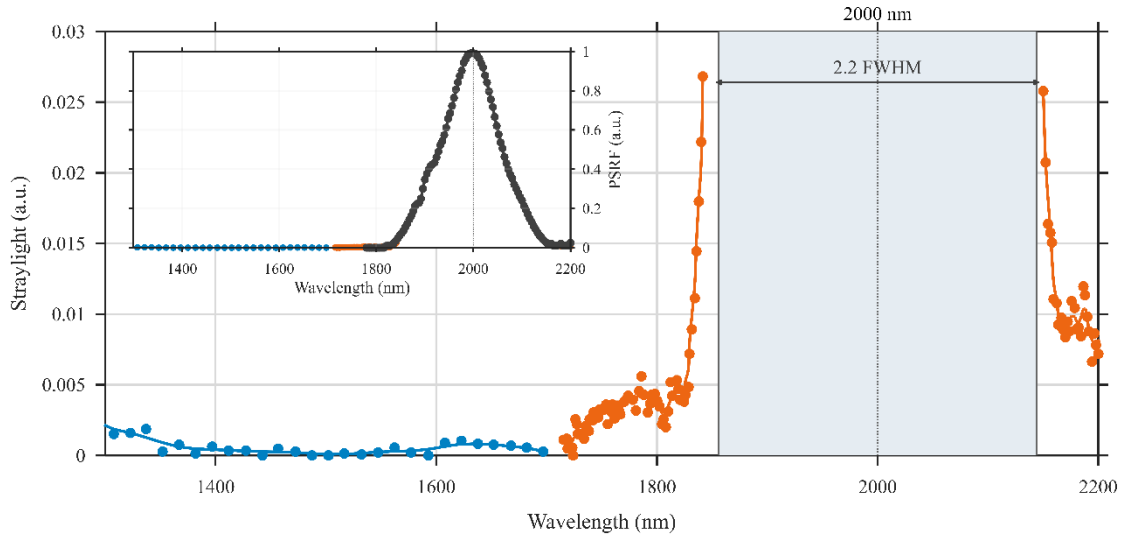


Figure 9. Measured straylight response obtained from monochromator scans beyond the useful PSRF region used to validate the non-sequential model and straylight analysis.

For each mirror position, the monochromator was scanned beyond the useful PSRF region, and the corrected signal was normalized to the useful integrated power. Prediction-to-measurement differences were approximately 50-60%. Although this does not constitute precision correlation of the low-level response, it confirms the spectral trend and compliance with the 1% straylight power requirement in both analysis and test. Large source corrections amplified noise at short wavelengths, while PSRF broadening near 2000 nm caused part of the nominal response to enter the straylight integral. Quantitative comparison was therefore limited to cases with reliable source correction and useful-zone definition. The model reproduced the measured plateau-like trend and the relative contributions of contamination and micro-roughness. Further work should increase spectral sampling, improve the test enclosure, stabilize the reference signal, and establish a consistent boundary between the nominal PSRF and straylight.

6 CONCLUSIONS

The dispersive-element trade-off supported selection of a three-prism fused-silica assembly for tunable solar filtering over the required spectral range. The resulting PSRF is governed by the dispersive behavior of the prism assembly, limb darkening, output-port vignetting, and the pupil distribution generated by the homogenizer.

The homogenizer reduces the transfer of input-pointing variations into the filtering response, although its alignment must be controlled using the characteristic ApStop pattern. Coupled optical, structural, and thermal analyses demonstrated that the PSRF and integrated output remained within the applicable allocations over the operational calibration interval. Micro-vibration and photo-elastic effects were non-driving.

Testing validated the spectral-filtering concept and supported correlation of the Zemax OpticStudio® and FRED® models. The measured PSRFs reproduced the predicted curve shapes and wavelength-dependent deformation, with FWHM differences between 1.5% and 8.7%. The measured straylight response reproduced the predicted spectral trend and order of magnitude, while both analysis and test retained margin against the 1% limit for the directly comparable cases.

The combined design, analysis, manufacturing, alignment, and test activities demonstrated the capabilities required for TRL 6 maturation of the SPC optical concept. The correlated models provide a substantiated basis for subsequent flight-design development, while the remaining low-level straylight differences identify the required refinements in detector-background correction, reference-signal stability, ray-tracing convergence, and PSRF-boundary definition.

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