

MHSRS²F-V2: A New-Generation Multidirectional Hyperspectral Remote Sensing Simulation Facility for HCRF Measurement

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Abstract

This paper introduces MHSRS²F-V2, a new-generation indoor facility for multidirectional hyperspectral remote sensing simulation and HCRF measurement. Built around an 8 m-diameter hemispherical lamp array, the facility integrates the solar simulation, skylight simulation, observation simulation, scene simulation, and integrated control subsystems. Hybrid illumination units provide broadband illumination over 350–2500 nm, with spectral correlation coefficients of approximately 0.928 and 0.912 for simulated sunlight and skylight, respectively. The facility supports coupled solar-skylight illumination, multidirectional observation, complex-scene construction, and both imaging and non-imaging payloads. Push-broom experiments produced spatially resolved HCRF image cubes of a physical sand-table scene and undisturbed rock samples, while multiangular ASD measurements revealed wavelength-dependent reflectance anisotropy. The results demonstrate the capability of MHSRS²F-V2 for controlled HCRF measurement and physical simulation of airborne and spaceborne hyperspectral remote sensing.

1. Introduction

Indoor remote sensing physical simulation facilities provide controlled experimental platforms for measuring surface spectral properties, investigating imaging mechanisms, and evaluating sensor observation performance. Compared with field measurements, laboratory facilities can maintain relatively stable illumination, prescribed observation geometry, and repeatable target conditions, thereby improving the repeatability and comparability of remote sensing experiments. Early laboratory systems generally used a single artificial light source and a non-imaging spectroradiometer to measure sample reflectance under specific illumination-viewing configurations. For example, RELAB was developed as a NASA-supported spectroscopy facility for measuring reflectance spectra of Earth and planetary materials (Pieters and Hiroi, 2004). With the increasing demand for directional reflectance characterization, laboratory spectrogoniometer systems such as GRIT, CLabSpeG, LAGOS, and DCaF were developed to acquire multiangular reflectance information under controlled source-target-sensor geometries (Dangel et al., 2003; Biliouris et al., 2007; Georgiev et al., 2008; Harms et al., 2017).

Most of these systems were mainly designed for bidirectional reflectance distribution function (BRDF) or bidirectional reflectance factor (BRF) measurements under single-source and collimated illumination. BRDF describes the ideal differential relationship between incident and viewing directions, whereas BRF is a measurable reflectance factor under a specified illumination-viewing geometry (Nicodemus et al., 1977; Schaepman-Strub et al., 2006). However, practical optical remote sensing observations are usually affected by both direct solar radiation and diffuse skylight, and the sensor observes the target within a finite field of view. Therefore, the measured quantity is often closer to the hemispherical-conical reflectance factor (HCRF) than to an ideal BRDF or BRF. In particular, diffuse skylight can make a non-negligible contribution to the total incident irradiance in the shortwave region (Gregg and Carder, 1990). This indicates that a physical simulation facility for realistic hyperspectral remote sensing experiments should not only provide multidirectional observation capability, but also reproduce coupled solar-skylight illumination over a broad spectral range.

To reproduce the complete remote sensing imaging process more realistically, imaging-oriented physical simulation facilities began to integrate illumination, scene, and imaging simulation. The Imagery Simulation Facility (ISF) developed by Itek Optical Systems employed three-dimensional scale-model scenes, imaging cameras, and an adjustable scene platform. Direct sunlight was simulated using high-intensity tungsten-halogen lamps, typically rated at 2000 W, while diffuse skylight was reproduced using a hemispherical array of 200 flood lamps. An additional haze source was introduced into the optical path to simulate atmospheric path radiance. By combining physical imagery with radiation-propagation calculations, target spectral data, and sensor models, ISF generated multispectral simulation imagery for sensor-design assessment and image-processing algorithm evaluation (Francis et al., 1993; Maver and Scarff, 1993).

To reduce the discrepancy between laboratory reflectance measurements and field remote sensing observations, Beihang University developed the Multidirectional Hyperspectral Remote Sensing Simulation Facility (MHSRS²F). The facility combined a solar simulator, a hemispherical skylight simulator, a goniometer, and a spectroradiometer to measure target HCRF spectra under coupled solar-skylight illumination (Zhao et al., 2019). MHSRS²F provided six representative skylight modes and simulated solar zenith angles from 15° to 60°. The irradiance uniformities of the solar and skylight simulation areas were approximately 89% and 88%-90%, respectively. Comparisons with field measurements in Dunhuang showed that, relative to conventional laboratory BCRF measurements, the HCRF spectra acquired using MHSRS²F reduced the mean amplitude and spectral-shape discrepancies from field HCRF spectra by 27% and 31%, respectively. These results demonstrated the feasibility of reproducing coupled solar-skylight illumination and measuring HCRF spectra under laboratory conditions. However, the original facility was primarily designed for pointwise reflectance measurements of small samples. Although its goniometer enabled multiangular point measurements, its scene-imaging mode was limited to fixed nadir observation and could not reproduce continuous imaging processes such as push-broom acquisition. Its effective illumination area, scene scale, and

spectral matching capability also restricted its application to hyperspectral imaging simulation of large and complex scenes.

To expand the effective illumination and observation coverage of the original facility for complex scenes and enhance its capability to simulate various airborne and spaceborne hyperspectral imaging modes, this paper introduces MHSRS²F-V2, a new-generation Multidirectional Hyperspectral Remote Sensing Simulation Facility. Built around an 8 m-diameter hemispherical lamp array and a central scene platform, the facility integrates the solar simulation, skylight simulation, observation simulation, scene simulation, and integrated control subsystems, with substantial improvements in solar and skylight spectral matching, illumination modes, and observation-angle range. By operating the solar and skylight simulation subsystems independently or jointly, MHSRS²F-V2 can support BRDF characterization or HCRF measurement according to experimental requirements, as well as hyperspectral imaging simulation of complex scenes under various airborne and spaceborne observation modes.

2. MHSRS²F-V2 Facility Architecture

2.1 Overall Configuration

Figure 1 presents the spatial layout and physical installation of MHSRS²F-V2. The facility adopts a scene-centered configuration in which the hemispherical steel-grid structure defines the main experimental volume. Skylight illumination units are distributed over multiple zenith layers of the hemispherical structure, while the solar simulation subsystem is mounted on an independent supporting frame outside the hemisphere and directed toward the central working area. The scene simulation subsystem is located at the center of the facility and accommodates different experimental objects, including material samples, reference panels, and sand-table scenes. The observation simulation subsystem is installed above the central region to carry the imaging payload and adjust its position and viewing direction relative to the scene.

The nominal scene center serves as the common geometric reference for the facility. The solar incident direction, skylight distribution, sensor line of sight, and scene orientation are defined within a unified coordinate system. This scene-centered arrangement maintains the spatial overlap among the direct-illumination area, diffuse skylight field, experimental scene, and sensor field of view. As illustrated by the photographs in Figure 1, different target types and imaging payloads can be installed within the same experimental volume, allowing illumination geometry, viewing direction, scene orientation, and payload configuration to be adjusted according to specific experimental requirements.

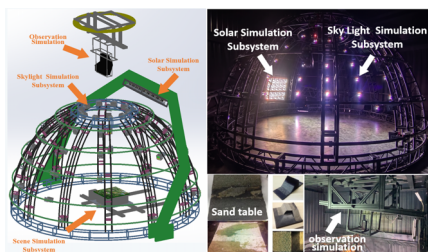


Figure 1. Overall configuration of MHSRS²F-V2

2.2 Solar and Skylight Simulation Subsystems

2.2.1 Lamp-array optimization scheme. The solar and skylight simulation subsystems adopt modular hybrid-source units to reproduce the spectral and spatial characteristics of direct sunlight and diffuse skylight. A candidate-source database was first established from the measured spectral irradiance and angular intensity distributions of metal-halide lamps, halogen lamps, white LEDs, and monochromatic LEDs. Metal-halide lamps provide a high-radiance broadband spectral baseline, halogen lamps supplement the near-infrared and shortwave-infrared regions, and LEDs compensate for local spectral differences, particularly in the visible and near-infrared regions. The solar and skylight illumination units follow the same spectral-synthesis principle, while different beam-shaping optics are used to produce narrow directional illumination for sunlight simulation and wider angular illumination for skylight simulation. Because the individual lamps are mutually incoherent, their time-averaged interference terms vanish, and the spectral irradiances generated by different sources can be added linearly. At a target-plane position $\mathbf{p}$, the synthesized spectral irradiance is expressed as:

$$E_{\text{sim}}(\lambda, \mathbf{p}) = \sum_{i=1}^K \sum_{j=1}^{n_i} a_{ij} E_{ij}(\lambda, \mathbf{p}) \quad (1)$$

where K is the number of source types, n_i is the number of sources of type i , a_{ij} is the operating or output coefficient of the j -th source of type i , and $E_{ij}(\lambda, \mathbf{p})$ is its spectral irradiance contribution at $\mathbf{p}$. This contribution accounts for the measured source spectrum, angular intensity distribution, source-target distance, and incidence angle. For spectral optimization at the nominal target center, Eq. (1) can be simplified as

$$E_{\text{sim}}(\lambda) = \sum_{i=1}^K n_i a_i E_i(\lambda) \quad (2)$$

The agreement between the synthesized spectrum and the target solar or skylight spectrum was evaluated using the Pearson correlation coefficient:

$$r = \frac{\sum_{\lambda} [E_{\text{sim}}(\lambda) - \bar{E}_{\text{sim}}][E_{\text{tar}}(\lambda) - \bar{E}_{\text{tar}}]}{\sqrt{\sum_{\lambda} [E_{\text{sim}}(\lambda) - \bar{E}_{\text{sim}}]^2 \sum_{\lambda} [E_{\text{tar}}(\lambda) - \bar{E}_{\text{tar}}]^2}} \quad (3)$$

where $E_{\text{tar}}(\lambda)$ is the target spectrum calculated for the prescribed atmospheric and solar-geometry conditions.

A two-stage genetic algorithm was employed to determine the source composition and spatial arrangement of each illumination unit. In the first stage, the chromosome encoded the number of each candidate source type. A randomly generated initial population was iteratively updated through fitness evaluation, roulette-wheel selection, crossover, and mutation. The optimization searched for the combination of source types and quantities that maximized the spectral correlation coefficient while satisfying the required irradiance and limiting the total number and cost of the sources. This stage determined the respective contributions of the metal-halide, halogen, white-LED, and monochromatic-LED components to the synthesized spectrum.

The optimized source types and quantities obtained in the first stage were retained in the second stage, in which the spatial

positions of the LEDs within each illumination unit were optimized. Each chromosome represented a permutation of the selected LED types over the available mounting positions. For every candidate arrangement, the spectral irradiance distribution over the target plane was calculated from the measured angular intensity distributions and the source-target geometry. The spatial nonuniformity of each spectral component was evaluated using the coefficient of variation,

$$CV_i = \frac{\sigma_i}{\bar{E}_i} \quad (4)$$

where $\bar{E}_i$ and σ_i are the mean and standard deviation of the irradiance produced by source type i over the target plane. The second-stage objective was to minimize the differences between the spatial distributions of the different spectral components:

$$J_2 = \sum_{i=1}^K [CV_{\text{ref}} - CV_i(\mathbf{x}_i)]^2 \quad (5)$$

where $\mathbf{x}_i$ denotes the spatial arrangement of source type i , and CV_{ref} is the nonuniformity of the reference broadband source distribution. This optimization suppresses wavelength-dependent spatial variations and ensures that the synthesized spectrum remains approximately consistent across the illuminated area.

The optimized solar and skylight units were replicated into modular arrays, enabling irradiance and illumination-mode adjustment while maintaining spectral composition.

2.2.2 Solar simulation subsystem. The solar simulation subsystem reproduces direct solar radiation using 25 hybrid illumination units arranged in a 5×5 planar array. Each unit integrates one metal-halide lamp, four halogen lamps, and 128 LEDs, forming an effective emitting aperture of approximately 125cm×125cm. The array is mounted on a motorized swing-arm mechanism outside the hemispherical structure. By rotating around the scene center while maintaining a source-target distance of approximately 3.8m, the subsystem keeps its optical axis directed toward the target and provides solar zenith angles from approximately 10° to 80°. The operating states of the individual units can also be adjusted to control the irradiance level.

Conventional solar simulators use an arc lamp and large collimating optics to generate a nearly parallel beam, making wide-angle rotation difficult. The present subsystem instead employs narrow-beam reflectors and total-internal-reflection lenses to provide quasi-collimated illumination with an approximately 10° divergence angle. Over 350–2500 nm, the spectral correlation coefficient with the target solar spectrum is approximately 0.928. It provides an effective illumination area of approximately 100 cm × 100 cm, with irradiance varying from 274 to 762 W/m² according to the solar zenith angle and source-output states. This corresponds to approximately 0.20–0.56 solar constants, assuming a solar constant of 1361 W/m². The irradiance nonuniformity is generally below approximately 11% (Du et al., 2023).

2.2.3 Skylight simulation subsystem. The skylight simulation subsystem reproduces multidirectional diffuse radiation from the upper hemisphere. It comprises 52 hybrid illumination units combining metal-halide lamps, halogen lamps, and LED arrays. These units are installed on six zenith-angle layers at approximately 15°, 30°, 45°, 60°, 75°, and 85° over an 8 m-diameter hemispherical steel-grid structure and are directed toward the central scene area.

Unlike the narrow directional illumination required for solar simulation, skylight illumination must cover the target from a broad range of incident directions. Therefore, each illumination unit has a divergence angle of approximately 40°, allowing the beams from adjacent units and zenith-angle layers to overlap over the central scene area and form a continuous and spatially uniform diffuse illumination field.

The subsystem covers the spectral range of 350–2500 nm, with a measured spectral correlation coefficient of approximately 0.912 relative to the target skylight spectrum. By controlling the number and positions of active units in different zenith-angle layers, nine representative skylight illumination modes can be generated. As listed in Table 1, the appropriate mode is selected according to the solar zenith angle and the prescribed combination of atmospheric profile and aerosol type. The target-plane irradiance is adjusted for each mode, with a relative deviation below approximately 4.9% from the corresponding target value. For all nine modes, the irradiance nonuniformity over the central scene area is below approximately 4.8%. The main parameters of the skylight simulation subsystem are summarized in Table 2.

solar zenith angle (°)	T+M	T+R	T+U	MLS+M	MLS+R	MLS+U	SAS+M	SAS+R	SAS+U
10	3	2	1	-	-	-	-	-	-
20	-	-	-	3	2	1	2	-	-
30	2	2	4	2	5	4	-	-	-
40	5	5	6	5	5	6	5	5	6
50	7	7	5	7	7	5	5	7	6
60	8	8	-	7	8	7	8	8	7
70	-	-	8	9	9	9	8	8	-
80	9	9	-	9	9	-	-	-	-

Table 1. Lookup table of skylight modes for coupled solar-skylight illumination under different atmospheric and aerosol conditions
Note: The numerical values denote the skylight illumination-mode numbers. T, MLS, and SAS represent tropical, mid-latitude summer, and subarctic summer atmospheric profiles, respectively; M, R, and U represent maritime, rural, and urban aerosol types, respectively. A dash indicates that no representative mode was assigned to the corresponding condition.

Parameter	Solar simulation subsystem	Skylight simulation subsystem
Simulated component	Direct solar radiation	Diffuse skylight radiation
Source composition	Metal-halide lamps, halogen lamps, and LED arrays	Metal-halide lamps, halogen lamps, and LED arrays
Number of illumination units	25	52
Spatial configuration	5×5 planar array	Six zenith-angle layers on an 8 m-diameter hemispherical steel-grid structure
Zenith-angle layers	Not applicable	Approximately 15°, 30°, 45°, 60°, 75°, and 85°
Effective emitting aperture or installation range	Approximately 125 cm × 125 cm	Distributed over the 8 m-hemispherical structure
Spectral range	350–2500 nm	350–2500 nm
Measured spectral correlation coefficient	Approximately 0.928	Approximately 0.912
Divergence angle	Approximately 10°	Approximately 40°
Distance to the target plane	Approximately 3.8 m	Determined by the positions of the units on the hemispherical structure
Effective illumination area	Approximately 100cm×100cm	Central scene area
Primary adjustment method	Adjustment of the incident direction and source output states	Adjustment of the number and positions of active units in each zenith-angle layer
Representative operating range or modes	Solar zenith angle range of approximately 10°–80°	Nine representative skylight illumination modes
Target-plane irradiance	Approximately 274–762 W/m ²	Adjusted according to the selected skylight illumination mode
Irradiance nonuniformity	Generally within approximately 11% over the principal operating range	Below approximately 4.8% for the nine representative modes
Principal function	Directional quasi-collimated illumination with a prescribed incident geometry	Multidirectional diffuse illumination from the upper hemisphere

Table 2. Main parameters of the solar and skylight simulation subsystems

2.3 Observation Simulation Subsystem

2.3.1 Motion Mechanism. The motion mechanism consists of an annular rotary frame, a linear guide rail, a viewing-zenith-angle adjustment frame, a roll-angle adjustment frame, and a payload mount. The rotary frame is installed on an annular support above the central scene and drives the complete payload-positioning assembly around the scene center. It provides a viewing-azimuth range of 0°–360°. Taking the scene center as the zero position, the linear guide rail translates the payload from −1 to +1 m, corresponding to a total travel distance of 2 m. The viewing zenith angle and roll angle can be adjusted within ±13° and ±11°, respectively. These mechanisms provide independent control of the payload position, viewing azimuth angle, viewing zenith angle, and roll angle.

The viewing azimuth angle is measured using a multi-turn encoder, while angle sensors provide position feedback for the viewing-zenith and roll-angle adjustment frames. The positioning accuracy of all three angular degrees of freedom is 0.02°. Position-locking and motion-limit devices are incorporated into the rotary frame and linear guide rail to improve positioning stability and operational safety. Through integrated control of payload translation and attitude, the mechanism supports both stationary observation at prescribed viewing geometries and dynamic observation with synchronized position-attitude changes.

2.3.2 Remote Sensing Payloads. The modular payload mount accommodates both non-imaging and imaging remote sensing instruments. Non-imaging payloads mainly include spectroradiometers, which acquire the radiance of the target and reference panel at prescribed viewing zenith and azimuth angles. By sequentially changing the viewing geometry, multidirectional spectral measurements can be obtained for HCRF measurement under coupled solar-skylight illumination or for BRDF characterization under directional solar illumination.

Imaging payloads include area-array hyperspectral cameras and line-array push-broom imaging spectrometers. Area-array sensors can acquire nadir or oblique images while the payload remains at a prescribed position and attitude. For line-array push-broom imaging, the payload is translated along the linear guide rail at a prescribed speed synchronized with the sensor line frequency. Integrated control of payload translation, viewing zenith angle, and roll angle enables five representative observation modes: nadir observation, fixed-point observation, push-broom imaging, motion-compensated imaging, and agile imaging. The subsystem can therefore reproduce multiple airborne and spaceborne hyperspectral imaging modes under controlled laboratory conditions.

The principal motion parameters, compatible payloads, and representative observation modes of the observation simulation subsystem are summarized in Table 3.

2.4 Scene Simulation Subsystem

2.4.1 System Configuration. The scene simulation subsystem is located at the center of the hemispherical structure and consists of two orthogonal linear guide rails, two stepper motors, a rotation stage, a tilting stage, and a scene-support platform. The two linear guide rails provide independent translations along the x- and y-directions, enabling the scene to be positioned within the overlapping region of the illumination field and the sensor field of view. The rotation stage adjusts the scene azimuth relative to the illumination direction, while the tilting stage changes the inclination of the scene surface to simulate sloped terrain and different target attitudes.

The translation, rotation, and tilting mechanisms can be operated independently or in coordination. This enables adjustment of the scene position, azimuth, and inclination without changing the prescribed payload geometry. Combined with the illumination and observation simulation subsystems, the scene simulation subsystem establishes repeatable source-target-sensor geometries for multidirectional spectral measurements and hyperspectral imaging experiments.

2.4.2 Sand-table scene construction. The scene-support platform accommodates both undisturbed samples and geometrically scaled physical sand-table models. Undisturbed samples, such as intact soil, vegetation, rock, and other natural materials, can be placed directly on the platform when preservation of their original composition, surface structure, moisture condition, and spectral characteristics is required.

For experiments involving larger or more complex ground scenes, a physical sand-table model can be constructed according to a prescribed geometric scale. The spatial arrangement, dimensions, and topographic relationships of targets and backgrounds are scaled according to the simulated ground coverage and imaging resolution. Real materials corresponding to the simulated surface types are used wherever possible, including natural soil, sand, rock, vegetation, water, and construction materials. This avoids relying solely on painted or printed substitutes and preserves the spectral reflectance, surface roughness, and scattering characteristics of the corresponding ground objects. Through flexible combinations of terrain, targets, and backgrounds, the subsystem can construct both homogeneous scenes and spatially heterogeneous scenes for controlled hyperspectral imaging experiments.

The configurable target forms and principal functions of the scene simulation subsystem are also summarized in Table 3.

Subsystem	Parameter	Specification or function
Observation simulation subsystem	Main motion mechanisms	Horizontal rotation, linear translation, viewing-zenith adjustment, and roll adjustment
	Viewing azimuth angle range	0°-360°
	Linear translation range	-1.0 to +1.0 m (2.0 m total travel)
	Viewing zenith angle range	-13° to +13°
	Roll angle range	-11° to +11°
	Angular positioning accuracy	Approximately 0.02° for the azimuth, viewing-zenith, and roll axes
	Compatible payloads	Imaging and non-imaging sensors
Scene simulation subsystem	Representative observation modes	Fixed-point spectral measurement, multiangular observation, push-broom scanning, and side-looking imaging
	Main adjustment mechanisms	Two-dimensional horizontal translation, rotation, and tilt adjustment
	Target forms	Undisturbed samples and scaled physical sand-table scenes
	Sand-table materials	Real materials selected to reproduce the spectral and structural properties of the corresponding ground objects
	Configurable scene elements	Terrain units, target objects, backgrounds, and reference panels
	Main functions	Scene positioning, source-target-sensor geometry adjustment, and construction of spatially heterogeneous scenes
Scene simulation subsystem	Representative applications	HCRF measurement, hyperspectral imaging simulation, and remote sensing experiments with complex scenes

Table 3. Main parameters and functions of the observation and scene simulation subsystems

2.5 Integrated Control Subsystem and Measurement Workflow

The integrated control subsystem coordinates illumination, payload positioning, scene adjustment, and hyperspectral acquisition within a repeatable workflow. During HCRF

measurement, the integrated control subsystem configures the solar illumination settings and the corresponding skylight mode, acquires the reference-panel and target radiances sequentially, and records the illumination geometry, viewing geometry, payload position, scene attitude, and integration time. For multidirectional measurements, data acquisition is repeated

according to a predefined angular sequence. These procedures support the traceability and repeatability of HCRF measurements conducted using MHSRS²F-V2.

3. HCRF Measurement Experiments and Results

Two complementary experiments were conducted to evaluate the HCRF measurement capability of MHSRS²F-V2. A push-broom hyperspectral imager was first used to acquire spatially resolved HCRF image cubes of a physical sand-table scene and undisturbed rock samples. An ASD spectroradiometer was then used to measure target HCRF at multiple viewing angles. Both experiments were performed under coupled solar-skylight illumination. For each measurement, the target and a calibrated reference panel were acquired under consistent illumination conditions, and the HCRF was calculated as

$$R_{\text{HCRF}}(\lambda, \theta_v, \phi_v) = \frac{L_t(\lambda, \theta_v, \phi_v)}{L_{\text{ref}}(\lambda, \theta_v, \phi_v)} R_{\text{ref}}(\lambda) \quad (6)$$

where L_t and L_{ref} are the measured radiances of the target and reference panel, respectively, and R_{ref} is the calibrated reflectance factor of the reference panel.

3.1 Push-Broom Hyperspectral HCRF Imaging of the Sand-Table Scene and Undisturbed Samples

The solar zenith angle was set to 20°, and skylight illumination mode 1 was selected. According to the coupled solar-skylight illumination lookup table in Table 1, this configuration represents a mid-latitude summer atmospheric profile with urban aerosols (MLS+U). The experimental targets included a physical sand-table scene representing the Huangshan copper-nickel mining area and undisturbed rock samples collected from the same area.

Hyperspectral data were acquired using a push-broom imaging spectrometer operating over 400–1000 nm with a spectral resolution better than 2.8 nm. The imaging spectrometer was mounted on the payload mount and adjusted to the prescribed viewing geometry. During image acquisition, the payload moved uniformly along the linear guide rail, with its translation speed synchronized with the line frequency of the imaging spectrometer. The illumination configuration and sensor settings were maintained throughout the scanning process.

A calibrated diffuse-reflectance reference panel was imaged under the same illumination and observation conditions. Eq. (6) was then applied pixel by pixel to convert the measured radiance data into HCRF. This procedure produced spatially resolved HCRF image cubes containing both the spatial distribution and spectral characteristics of the experimental targets.

Figure 2 presents the HCRF image cubes and representative spectra of the physical sand-table scene and undisturbed rock samples from the Huangshan copper-nickel mining area. Within the reliable spectral range of 400–900 nm, the selected sand-table region exhibits a relatively high HCRF: it decreases from approximately 0.55 at 400 nm to approximately 0.39 near 440 nm and then gradually increases to approximately 0.5–0.6 toward 800 nm, followed by a local decrease near 850 nm. In contrast, the selected rock sample has a substantially lower HCRF, increasing gradually from approximately 0.08 at 400 nm to approximately 0.18 near 850 nm. The spatial contrasts in the HCRF image cubes and the distinct spectral levels of the two regions demonstrate the capability of the push-broom hyperspectral imager to resolve reflectance differences among

materials. Both spectra show an abrupt increase near 900 nm. Because this discontinuity occurs at nearly the same wavelength for two different targets and is close to the long-wavelength limit of the imaging spectrometer, it is attributed to an instrument-related response anomaly rather than an intrinsic reflectance feature of the samples. Therefore, values beyond approximately 900 nm were not used for spectral interpretation.

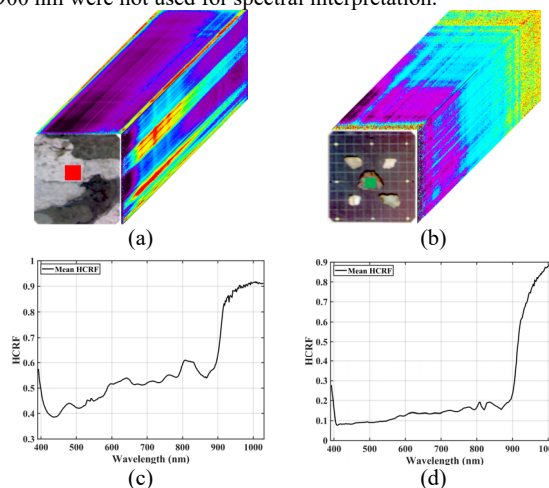


Figure 2. Push-broom hyperspectral HCRF imaging results for targets from the Huangshan copper-nickel mining area: (a) HCRF image cube of the physical sand-table scene; (b) HCRF image cube of the undisturbed rock samples; (c) and (d) mean HCRF spectra extracted from the red and green regions of interest shown in (a) and (b), respectively.

3.2 Multiangular HCRF Measurement of the Undisturbed Rock Sample

The undisturbed rock sample identified by the green region of interest in Figure 2(b) was selected for the multiangular HCRF experiment. The solar zenith angle was set to 30°, and skylight illumination mode 4 was selected. According to the lookup table in Table 1, this configuration corresponds to a mid-latitude summer atmospheric profile with urban aerosols (MLS+U). The solar and skylight simulation subsystems were operated simultaneously to establish coupled solar-skylight illumination, and the illumination configuration and source-output states were maintained throughout the experiment. A radiometrically calibrated ASD FieldSpec Pro spectroradiometer covering 350–2500 nm was used for spectral acquisition. After instrument warm-up, dark-current correction and white-reference calibration were performed.

The viewing zenith angles were set to 0°, 15°, 30°, 45°, and 60°, while the viewing azimuth angles, referenced to the solar azimuth direction, ranged from 0° to 315° at 45° intervals. At each viewing geometry, the reflected radiances of a calibrated reference panel and the undisturbed sample were measured successively under unchanged illumination conditions. The HCRF was calculated using Eq. (6), and the detector discontinuities near 1000 and 1800 nm were removed using a dynamic parabolic correction.

Figure 3 shows the directional HCRF distributions at 550, 850, 1650, and 2200 nm. The measured HCRF ranges are approximately 0.018–0.117, 0.043–0.125, 0.038–0.141, and 0.030–0.120, respectively. Clear azimuthal asymmetry is observed at all four wavelengths. Higher HCRF values are

mainly distributed around viewing azimuth angles of 180° – 225° , particularly at large viewing zenith angles, whereas lower values generally occur near 0° – 45° and 135° . Additional local maxima appear near 315° at 850, 1650, and 2200 nm. The directional contrast is more pronounced in the shortwave-infrared bands, indicating that the reflectance anisotropy of the undisturbed sample varies with wavelength. These results demonstrate the capability of MHSRS²F-V2 to measure multiangular HCRF under controlled coupled solar-skylight illumination.

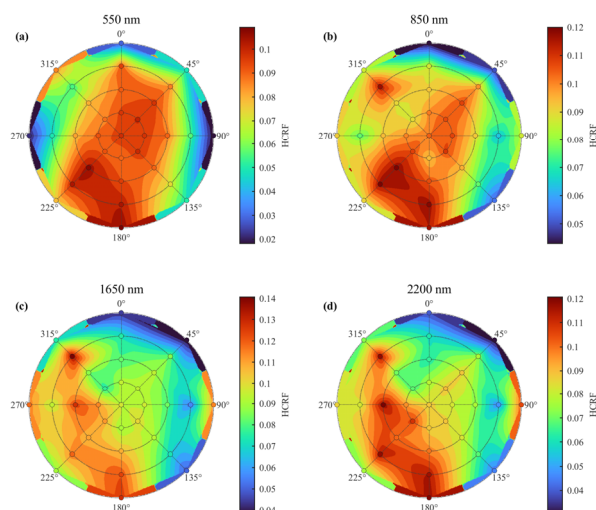


Figure 3. Directional HCRF distributions of the undisturbed rock sample under coupled solar-skylight illumination at a solar zenith angle of 30° : (a) 550 nm; (b) 850 nm; (c) 1650 nm; and (d) 2200 nm. The circles represent the measured viewing geometries, and the distributions between measurement directions were obtained by spatial interpolation. The color scale is independently adjusted for each wavelength.

4. Conclusions

Conventional laboratory reflectance facilities are mainly designed for BRDF or BRF measurements under single-source illumination and are therefore limited in reproducing the coupled solar-skylight conditions, finite sensor field of view, and complex scene configurations encountered in practical hyperspectral remote sensing. Although the original MHSRS²F demonstrated the feasibility of laboratory HCRF measurement under coupled solar-skylight illumination, its pointwise measurement mode, limited illumination area, and fixed-nadir scene observation restricted its application to large and complex scenes and continuous hyperspectral imaging simulation.

To overcome these limitations, this study developed MHSRS²F-V2, a new-generation indoor multidirectional hyperspectral remote sensing simulation facility. The system expands the illumination and observation coverage through an 8 m-diameter hemispherical lamp array, a central scene platform, and integrated solar simulation, skylight simulation, observation simulation, scene simulation, and control subsystems. Its independently controllable solar and skylight subsystems support both single-source BRDF characterization and coupled-illumination HCRF measurement, while its flexible observation geometry accommodates both imaging and non-imaging sensors. The experimental results verified these enhanced capabilities. Push-broom hyperspectral imaging acquired spatially resolved HCRF image cubes of a physical sand-table scene and

undisturbed rock samples, demonstrating continuous imaging simulation for spatially heterogeneous targets. Multiangular ASD measurements further revealed wavelength-dependent reflectance anisotropy under coupled solar-skylight illumination, confirming the facility's ability to characterize directional HCRF behavior under more realistic illumination conditions.

MHSRS²F-V2 extends indoor physical simulation from pointwise reflectance measurement to multidirectional hyperspectral observation of complex scenes. The facility provides a controlled and repeatable platform for investigating illumination-target-sensor interactions, evaluating airborne and spaceborne hyperspectral sensor configurations, and supporting the development and validation of hyperspectral image-simulation and processing methods.

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