The SOLAR-HRS New High-Resolution Solar Spectra for Disk-Integrated, Disk-Center, and Intermediate Cases

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1 – Abstract

The solar spectrum at the Top Of the Atmosphere (TOA) contains crucial data for fields such as solar physics, astronomy, and geophysics. Accurately determining high-resolution solar reference spectra, whether they are disk-integrated, disk-center, or intermediate cases, is a new challenge and is of primary importance for all applications where spectral solar radiation needs to be evaluated. These spectra are also essential for interpreting remote sensing measurements that rely on sunlight, such as those obtained by Earth observation satellites or spacecraft exploring other planets. We will present the implementation of multiple new solar irradiance reference spectra that have high resolution and are representative of solar minimum conditions. We developed the SOLAR high-resolution extraterrestrial reference spectra (SOLAR-HRS disk-integrated spectra) by normalizing high-spectral-resolution solar line data to the absolute irradiance scale of the SOLAR-ISS reference spectrum. The resulting unique SOLAR-HRS disk-integrated spectrum has a spectral resolution varying between 0.001 and 1 nm in the 0.5–4400 nm wavelength range. We also implemented a new high-resolution solar spectrum at the disk-center, covering a range of 650–4400 nm with a spectral resolution of 0.001 to 0.02 nm. We further expanded our analysis by producing several solar spectra for ten different solar view angles ranging from μ = 0.9 to μ = 0.05 (SOLAR-HRS intermediate cases). Finally, we developed new Merged Parallelized Simplified ATLAS spectra (MPS-ATLAS) based on solar modeling with Kurucz and Vald3 solar linelists for both the disk-integrated and disk-center spectra. One of the objectives of implementing all these new solar spectra is to fulfill the requirements of the MicroCarb space mission, which focuses on measuring greenhouse gas emissions. The solar data from this study are openly available.

2 – Introduction and context

The solar spectrum is the distribution of electromagnetic radiation emitted by the Sun as a function of wavelength, ranging from gamma rays to radio waves. It can be categorized into several bands, namely, gamma-ray (10 fm to 1 pm), X-ray (1 pm to 10 nm), ultraviolet (10–380 nm), visible (380–780 nm), infrared (780 nm to 1 mm), microwave (1–15 mm), and radio wavelengths (0.1 mm to 100 m). An accurate knowledge of the solar spectrum represents an important input for various disciplines and areas, including astronomy and astrophysics, solar physics, atmospheric science, remote sensing and its application and solar energy.

The solar spectrum provides essential data for studying the physical processes that occur in the Sun, such as nuclear fusion, energy transfer, and magnetic field generation. By analyzing the solar spectrum in detail, we can obtain valuable information about the chemical composition, temperature, and density of various layers in the solar atmosphere, as well as the presence of magnetic fields and other phenomena. This knowledge is crucial for advancing our understanding of the Sun. Three main kinds of solar spectra are of interest:

- ❑ The disk-integrated solar spectrum (Figure 1) and its variations over time, which are important for understanding the solar variability and its underlying mechanisms.
- ❑ The disk-center solar spectrum (with the deepest and warmest layers at the center) and limb darkening, which are important for the construction and verification of solar model atmospheres and therefore for a better understanding of the solar atmosphere.
- ❑ Solar spectra for different solar view angles, which are crucial for our understanding of both spatially resolved solar spectral radiance and full-disk spectral irradiance.

Various solar reference spectra exist from space-based measurements but none provide a very high resolution (<0.01 nm) solar spectrum spanning a wide range of wavelengths. The **SOLAR-HRS reference solar spectrum representative of a solar minimum** seeks to meet this requirement and is unique. It is based on SOLAR-ISS reference spectrum (absolute determination from 300 to 3000 nm), Quality Assurance of Spectral Ultraviolet Measurements In Europe Fourier Transform Spectrometer (QASUMEFTS) solar irradiance observations (from 300 to 380 nm), and solar pseudo-transmittance (from 300 to 4400 nm). The solar pseudo-transmittance spectrum (Toon, 2014) is obtained from an empirical solar linelist, which have been generated by simultaneous fitting of ATMOS, MkIV, Kitt Peak, Denver U, and Total Carbon Column Observing Network (TCCON) spectra and by a telluric absorptions fit using the HITRAN linelist (any remaining airmass-independent absorptions were attributed to the Sun).

The SOLAR-HRS reference solar spectrum will be compared to TSIS-1 HSRS (Coddington et al., 2021), and the 1D MPS-ATLAS model with Kurucz linelist. It is based on the Merged Parallelised Simplified ATLAS code (Witzke et al., 2021). From solar parameters (Teff, log g, Fe/H+ abundances, …), MPS-ATLAS calculates solar spectra together with their centre-to-limb variations (CLV). Then, we can obtain disk-centre and disk-integrated spectra. These CLV for typical wavelengths could be compared to models (Neckel, 2005) or measurements with space-based instruments (PICARD/SODISM).

One of our objectives is also to provide high resolution spectra for the MicroCarb mission, which is designed to map sources and sinks of carbon dioxide (CO2). This mission requires high resolution solar spectrum according to four wavelengths bands (Tables 1 and 2). The MicroCarb spectra inversion tool, 4ARTIC, is based on the radiative transfer code 4AOP, one of the inputs of which is the solar spectrum et high resolution. 4ARTIC estimates the geophysical state (profiles of CO2, H2O, aerosols, surface albedo, surface pressure) by minimizing the difference between the theoretical spectrum and the measured spectrum. A good knowledge of the radiometric level of the continuum of this spectrum is essential in order to not disturb the inversion by erroneous residues. A study of the MicroCarb team shows that an error in the radiometric level of the solar spectrum will result, during the inversion, by a confusion on the levels of light reflected by the surface and of light scattered by the atmosphere, which will induce an error on the estimated CO2. Low-frequency variations of the continuum can also disrupt the estimation of surface albedo or aerosols, with an impact on CO2. The precision sought on the **absolute level of the solar continuum is 1%**. A good knowledge of the positions and shapes of the solar lines is also necessary to minimize the residues which can otherwise disturb the inversion. In particular, poorly modeled solar lines coinciding with atmospheric lines are particularly difficult to detect. The expected line shape knowledge calibration precision is 0.1% (integral of the difference between the model line and the true line).

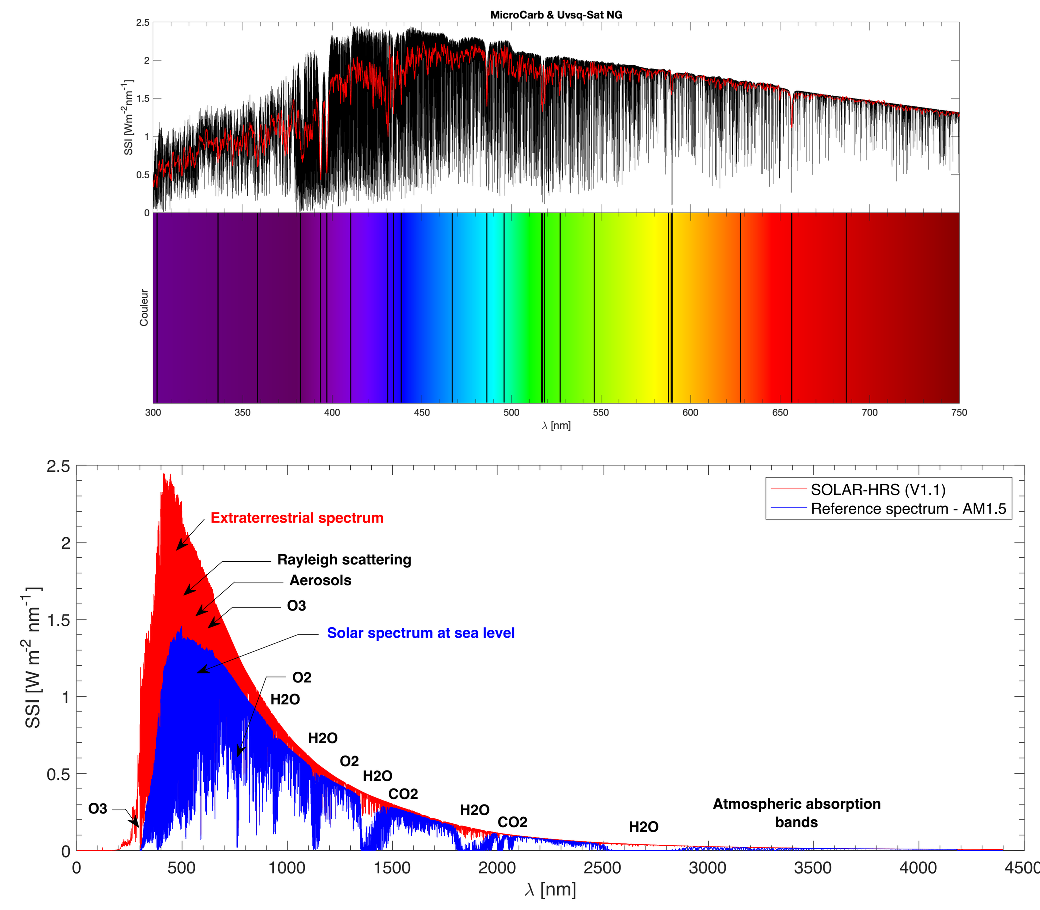


Figure 1. Disk-integrated solar spectra at one astronomical unit (SOLAR-HRS, SOLAR-HRS at air mass 1.5) from a few nm to 4.4 µm wavelengths, and absorption bands of atmospheric gases.

Parameter	B1	B2	B3	B4
λ_{min} (nm)	758.281	1596.772	2023.018	1264.630
λ (nm)	763.500	1607.900	2037.100	1273.400
λ_{max} (nm)	768.817	1618.946	2051.116	1282.191
FWHM (nm)	0.02966200	0.06226379	0.07900023	0.04932027
Sampling (nm)	0.01033519	0.02169470	0.02752621	0.01724485
Atmospheric gas	O_2	CO_2	CO_2	O_2

Table 1. MicroCarb observation wavelength bands.

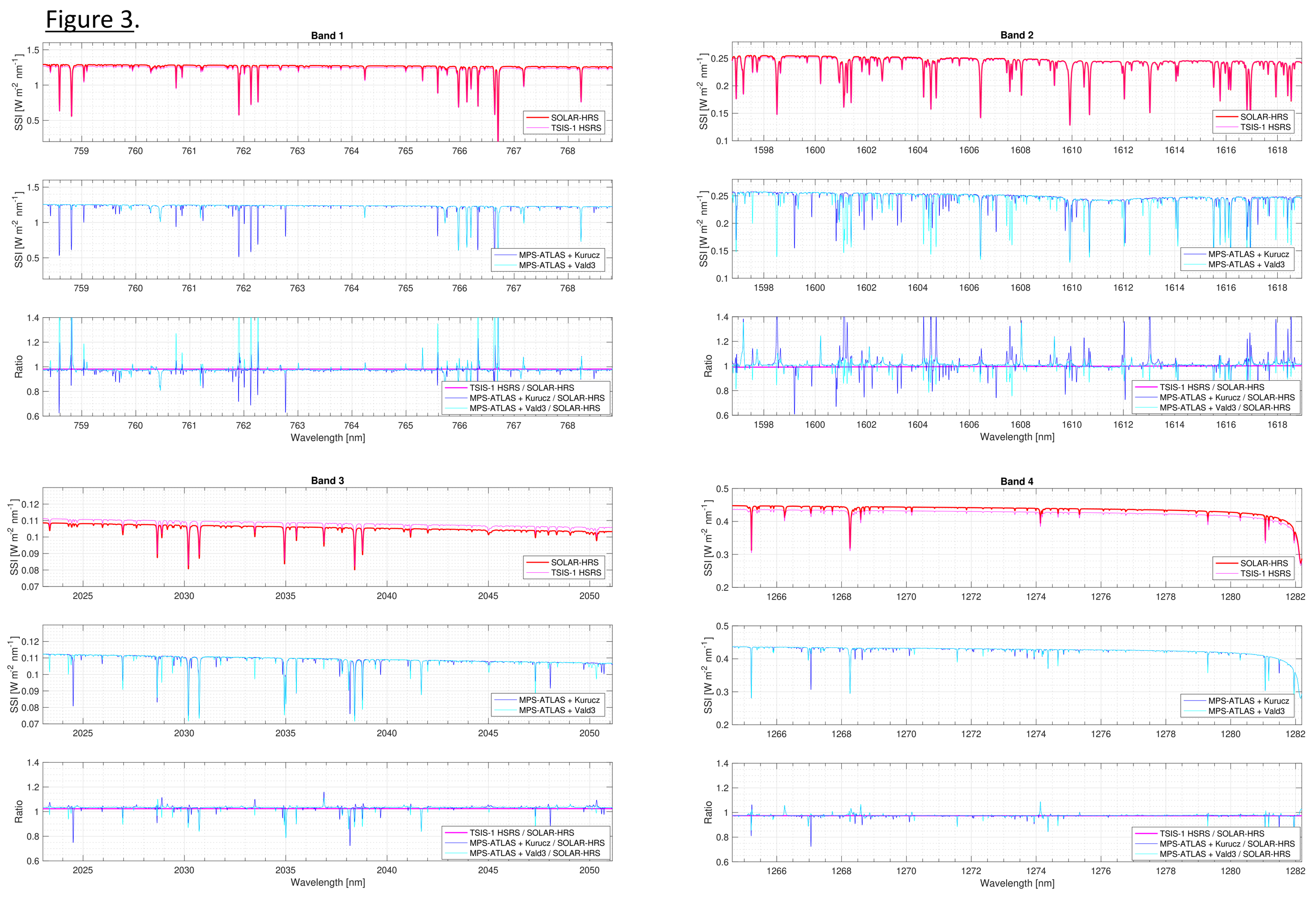
Parameter	SOLAR-HRS	B1, B2, B3, and B4
Wavelength range (nm)	0.5–4400	763.5, 1607.9, 2037.1, and 1273.4
Sampling resolution (nm)	<0.1	<0.004
Spectral resolution (nm)	<0.1	0.004
Absolute uncertainty (%)	<2	1
Central line position (nm)	$<10^{-4}$	10^{-5}
Fraunhofer line shape (%)	<1	0.1

Table 2. Scientific requirements for an accurate Disk-integrated solar spectrum.

3 – Results & comparisons to other data set

In this section, we introduce all the solar spectra we have developed (Table 3) by normalizing high-resolution solar line data to the absolute irradiance scale of the SOLAR-ISS reference spectrum, as well as those derived from modeling (Figure 2). Additionally, we conduct comparisons with independent datasets.

Figure 3.



http://doi.latmos.ipsl.fr/DOI_SOLAR_HRS.v1.1.html

Dataset Name	Data Type	Wavelength Coverage	Spectral Resolution	Sampling
SOLAR-HRS Disk-integrated spectrum	Composite Solar spectral irradiance	0.5–4399.1 nm	SOLAR-ISS (<300 nm): <1.0 nm QASUMEFTS (300–380 nm): <0.025 nm SPTS (>380 nm): <0.01 nm	<0.02 nm
SOLAR-HRS Disk-center (μ = 1.0)	Composite Solar spectral irradiance	650.0–4399.1 nm	SPTS: <0.01 nm	<0.02 nm
SOLAR-HRS Intermediate cases Solar positions μ = 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.05	Composite Solar spectral irradiance	650.0–4399.1 nm	SPTS: <0.01 nm	<0.02 nm
SOLAR-HRS AM1.5 Disk-integrated spectrum	Composite Solar spectral irradiance	0.5–4399.1 nm	SOLAR-ISS (<300 nm): <0.1 nm QASUMEFTS (300–380 nm): <0.025 nm SPTS (>380 nm): <0.01 nm	<0.02 nm
SOLAR-HRS AM1.5 (air) Disk-integrated spectrum	Composite Solar spectral irradiance	0.5–4399.1 nm	SOLAR-ISS (<300 nm): <0.1 nm QASUMEFTS (300–380 nm): <0.025 nm SPTS (>380 nm): <0.01 nm	<0.02 nm
MPS-ATLAS-Kurucz Disk-integrated spectrum	Solar model	250.0–5000.0 nm	<0.01 nm	<0.01 nm
MPS-ATLAS-Kurucz Disk-center (μ = 1.0)	Solar model	250.0–5000.0 nm	<0.01 nm	<0.01 nm
MPS-ATLAS-Vald3 Disk-integrated spectrum	Solar model	250.0–5000.0 nm	<0.01 nm	<0.01 nm
MPS-ATLAS-Vald3 Disk-center (μ = 1.0)	Solar model	250.0–5000.0 nm	<0.01 nm	<0.01 nm

Table 3. List of SOLAR-HRS and MPS-ATLAS spectra. All solar spectra are given at one astronomical unit. Meftah et al., 2023.

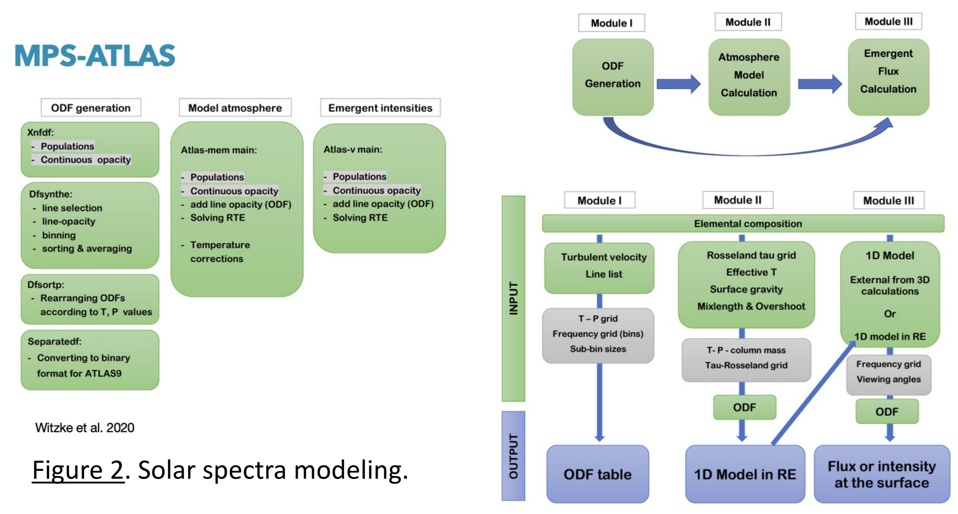


Figure 2. Solar spectra modeling.

Figure 4.

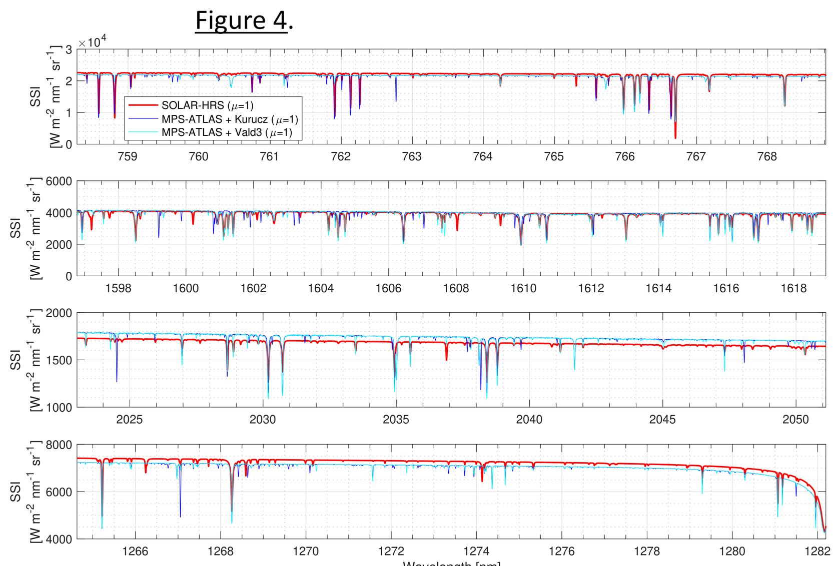


Figure 5.

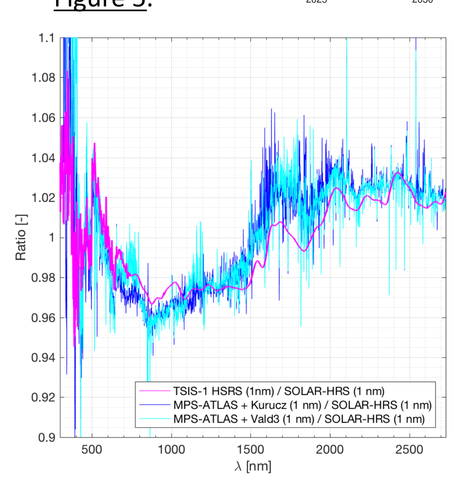
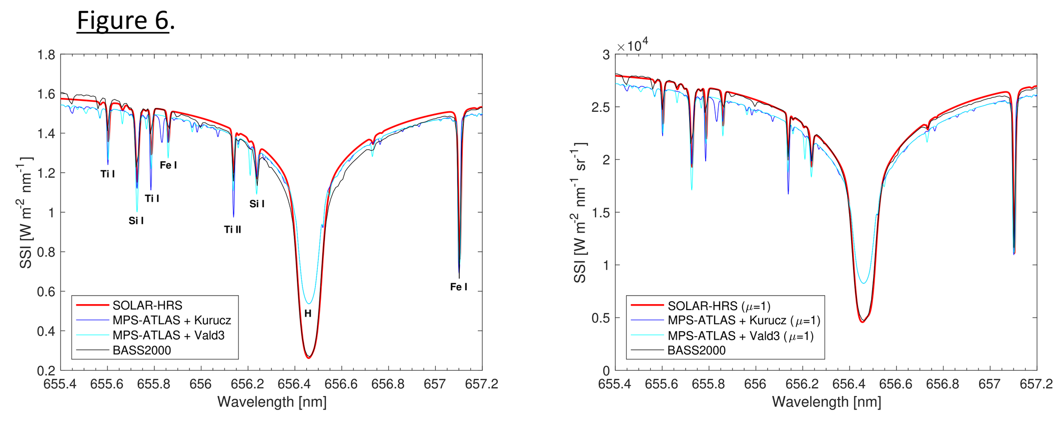


Figure 6.



4 – Conclusions

SOLAR-HRS (disk-integrated) represents a spectrum characteristic of solar minimum conditions (see current status in Table 4). The agreement with the TSIS-S HSR spectrum is excellent. Moreover, we've implemented new high-resolution disk-integrated solar spectra based on solar modeling (MPS-ATLAS) using Kurucz and Vald3 solar linelists. However, agreement with the 1D (MPS-ATLAS) model is less convincing, primarily due to limitations in the input solar linelists from Kurucz and Vald3. We eagerly await observations from MicroCarb (scheduled to launch in 2025) across its four bands to validate the various developed spectra (SOLAR-HRS and MPS-ATLAS). We have also created a unique new solar SOLAR-HRS disk-center spectrum in the 650.0–4400.0 nm wavelength range, along with several solar spectra (SOLAR-HRS intermediate cases) for ten different solar view angles from μ = 0.9 to μ = 0.05. Additionally, we have developed new solar spectra based on models (MPS-ATLAS) to facilitate comparisons. These advancements underscore the necessity for new European spacecraft instruments (SOLSPEC NG, SOLSPEC VIS, SOLSPEC NIR) to observe the Sun with utmost accuracy.

Parameter	B1, B2, B3 and B4	Current status
Sampling resolution [nm]	< 0.004	OK
Spectral resolution [nm]	0.004	OK
Absolute uncertainty [%]	1	NOK ⟹ 1.94% for B2
Central line position [nm]	10^{-5}	Difficult to assess
Fraunhofer lines shape [%]	0.1	NOK ⟹ 0.5% for all bands

Table 4. Current status of SOLAR-HRS (disk-integrated)

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