Selection of a solar reference spectrum for GLI's reflective bands

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Abstract

For remote sensing of the Earth in the ultraviolet (UV), visible (VIS) and short-wave infrared (SWIR), the extraterrestrial solar spectral irradiance (E_{sun} (λ)) has to be known with high accuracy. However, the discrepancy in currently available zero air mass E_{sun} (λ) data is large due to two sources of uncertainties: the variation of the solar activity and uncertainties in the experimental data.
NASDA's global orientated GLI sensor will be launched in 2002, hence it became necessary to select a solar spectrum which is suitable for GLI's reflective channels in terms of spectral coverage, total error etc. This is why a study was performed at NASDA, EORC to select a solar irradiance spectrum by comparing various spectra weighted by the spectral response functions of GLI's reflective channels. As a result the experimental solar irradiance data published by Thuillier in 2001 were selected because this data seems to have the so far smallest error (RMS error in VIS: 1.5 - 2%), a suitable spectral range and resolution for GLI's reflective channels (200–2500 nm) and $\Delta\lambda$ = 1 nm (200–870nm) and 20 nm (870–2500nm).

1. Introduction

Global Imager (GLI):
GLI is an optical sensor planned for launch for on ADEOS-2 in 2002 (Nakajima et al.-1998). It will observe solar light reflected from the Earth's surface including land, ocean and cloud, or infrared radiation, globally and frequently measures the physical data such as surface temperature, vegetation distribution, and ice distribution. These data may be used for acquiring the global circulation of carbon, monitoring cloud, snow, ice and sea surface temperature, and grasping the primary marine production. GLI has 23 channels in the UV and visible and near-infrared region (VNIR), 6 channels in short wavelength infrared region (SWIR), and 7 channels in middle and thermal infrared region (MTIR) for its multi spectral observation. The ground resolution is 1 km at the nadir, a part of the channels in VNIR and SWIR has a resolution of 250 m at the nadir which will be used for observing vegetation and clouds. The observation region by mechanical scanning is 12 or 48 pixels (12 km) in the along-trade direction and 1600 km in the cross-track direction. The cross track scanning is performed by rotating the scanning mirror mechanically. Its tilting angle is about +20 degree or –20 degree from the progressing direction.

Uncertainty in extraterrestrial solar irradiance data
For selecting a suitable extraterrestrial solar reference spectrum (i.e., zero air mass or the absence of atmospheric attenuation at one astronomical unit from the sun) for GLI reflective channels two sources of uncertainties have to be taken into account: the variation of the solar activity and uncertainties in the

experimental data. The variation of the solar activity depends on time (e.g. the solar output change depending on the 11-year solar cycle and the 27-day solar rotation). This change causes a variation of the solar constant (E_0 = 1366.1 Wm^{-2}) in a magnitude of about 0.4 % (maximum-to-minimum rage: 1363 to 1368 Wm^{-2} ; Fröhlich & Lean-1998). The solar output varies with time at a rate of change which is a function of the wavelength. In the UV (1-400nm) the changes are in the order of 1-10% and in the VIS and SWIR less than 1%. This solar variation in the VIS-SWIR is small when compared to the discrepancies in absolute spectral irradiance ($Wm^{-2}\mu m^{-1}$) between various experimental data. The uncertainties in the experimental data are attributed to (1) discrepancies between calibration standards and (2) problems in the measurement procedure and ageing.

1. Unfortunately there is a divergence between national calibration standards sources which reach values of ± 2% in the VNIR spectral region. This discrepancy depends on the wavelength. In the UV and IR higher uncertainties are expected (Woods et al.-1996, Riley & Bailey-1997).
2. Discrepancies might occur because of uncertainties in the measurement procedures and solar observatory location, e.g. for ground observatories the absorption bands have to be accounted for and an ageing problem occurs for space sensors when performing the measurements in space environment.

Objective of this investigation:

It becomes necessary to select a solar irradiance spectrum for the GLI mission (e.g. absolute solar calibration) which appears to be the most suitable. For this selection, the following science-driven criteria achieved highest priority: (1) spectral coverage and resolution, (2) estimated errors and (3) expected updates (improvements) of the data.

1. The spectral coverage and resolution should be suitable for the 29 reflective channels of GLI, i.e. the data should cover the UV–VIS–SWIR (350–2500nm). The spectral resolution in the UV–VIS–NIR should be in the order of $\Delta\lambda$ = 1nm due to the occurrence of large absorption lines (Frauenhofer Lines). Coarser resolution is required in the SWIR (less Frauenhofer lines)
2. The total error of the selected solar spectrum should be as small as possible and the data should be inter-compared with other experiments.
3. To reduce the remaining error of the data, technical improvement of the experiments should be carried out, e.g. follow-on experiments, long-term observations. Also updates in case of solar irradiance changes should be provided (especially for GLI's UV channel at 380nm).

This is why an overview on solar-irradiance sources was performed. After the selection of candidate data sets, the solar irradiance data were compared using the response functions of 29 GLI reflective bands (UV-VIS-SWIR).

2. Remote sensing missions and the applied solar reference data

In 1984, Neckel & Labs published a solar spectrum which was based on long-term observations of absolute solar intensities (from Labs & Neckel-1962 and successive papers till Neckel & Labs-1984). The 1984 values became reference data for many science communities (such as the remote sensing community). Also Wehrli used the Neckel & Labs-1984 data for his 'standard spectrum' published by the World Radiance Center (WRC) in Wehrli-1985. Later parts of this spectrum were integrated in well-known atmospheric modeling codes such as LOWTRAN (Kneizys et al.-1996) and 5–S (Tanre et al.-1990).

Recently, new experiments on various space platforms have been performed, what made parts of the remote sensing community to shift from the 'standard spectrum' to new and improved data sets published in Thuillier et al.-1998 or Thuillier-2001a. These experiments are carried out on space-based platforms, which allow an observation of the Sun without absorbing influence of the Earth's atmosphere.

The following table gives an overview on the applied solar irradiance spectra for various remote sensing missions.

Table 1: Overview of remote sensing missions and applied solar irradiance data.

Mission	Launch	Applied Solar Spectrum	Spectral range of the solar spectrum	Reference
MOS-IRS	1996 Mar	Neckel & Labs 1984	400–1250nm	Suemnich & Schwarzer-1998
SeaWiFS	1997 Aug	Neckel & Labs 1984	400–1250nm	Barnes et al.-1999
SPOT	since 1999	Thuillier et al. 1998	350 – 870nm	Dinguirard & Slater-1999
MODIS	1999 Dec	Thuillier et al. 1998 Neckel & Labs 1984 Smith & Gottlieb 1974	350 – 800nm 800 – 1100nm 1100 – 2500nm	MODIS-2000 (NASA-MCST Homepage)
MERIS	2002	Thuillier et al. 2001a	199 – 2493 nm	Delwart-2001
GLI	2002	Thuillier et al. 2001a	199 – 2493 nm	

3. Overview on solar irradiance data sets

3.1. From the standard WRC spectrum to MODTRAN 4.0

The standard spectral solar irradiance
The World Radiation Center (WRC) published in 1985 a standard spectral solar irradiance curve. This spectrum was compiled by Wehrli-1985 and is based on publications of Brasseur & Simon-1981 for the spectral range from 200 to 310 nm, Arvesen, et al.-1969 for 310–330nm, Neckel & Labs-1984 for 330–869 nm, and Smith & Gottlieb-1974 for 870nm–20µm. Between different spectra—at the wavelength limits—the values were forced to be equal and the resulting complete spectrum was scaled to yield a solar constant of 1367 Wm^{-2}. This WRC spectrum was adopted by the WMO (World Meteorological Organisation) as a standard solar irradiance curve. However, it became obvious, that this spectrum is difficult to assess as described in Schmid et al.-1998: An agreement has been forced at the wavelength limits between different spectra, the whole spectrum has been scaled, the work of Brasseur & Simon-1981 is again a compilation of measurements performed by several authors, and in some cases it is unclear if the authors state 1σ, 2σ, or 3σ uncertainties.

From MODTRAN 2 to MODTRAN 4.0
Parts of this standard spectral solar irradiance curve had been used in the atmospheric transmittance radiance programs LOWTRAN 7 and MODTRAN 2 which were released in 1992 (Kurucz–1995) by the Air Force Phillips Laboratory (APL). Thereupon, Gao & Green–1995 found that the standard spectrum contains many absorption features in the 2.0–2.5-µm region that are not of solar origin by comparing high-resolution solar occultation spectra from the shuttle-borne Atmospheric Trace Molecule Spectroscopy experiment. Moreover, Gao & Green–1995 show that an Earth atmospheric oxygen band at 1.268 µm and a water-vapor band near 0.94 mm seems to be present in the Wehrli-1985 curve. As stated in Schmid et al.-1998, the researchers at the APL and at Harvard Smithsonian—worried by the findings of Gao & Green–1995—have made major efforts to produce a new extraterrestrial solar irradiance curve covering the spectral region from UV to the long-wave IR (200 nm to 200 µm). This refined solar spectrum has been released by APL for public use as a part of MODTRAN 3 (Kurucz–1995). Gao & Green–1995 state that many problems they describe in their paper have been corrected in the new APL solar spectrum (Schmid et al.-1998)
However, the synthetic spectrum from Kurucz–1995 as used in MODTRAN 3 exhibited large oscillations in the UV (amplitude ≥ 10%) when compared with experimental data. In MODTRAN 3.5 version 1.2, a correction in the range from 300 to 350 nm was applied to the Kurucz spectrum. Although there is no major change of the applied solar irradiance spectrum version from MODTRAN 3.7 to the most recent version MODTRAN 4.0 (Acharya et al.-1998), the current version allows to select a solar irradiance spectrum from a database, which obtains various original and corrected sources, such as Kurucz-1995, Thuillier-1998 and Woods et al.-1996. However, it is difficult to access the modifications and applied compilations of the different spectra. As a result of lacking error estimations for the synthetic spectra, a wavelength-independent RMS uncertainty can be adopted arbitrarily: UV > 5%; VIS < 5% and SWIR > 5%.

Conclusion

The most recent versions of solar irradiance data available in MODTRAN 4.0 database are a good basis for synthetic solar irradiance data based on the spectral solar irradiance curves from various sources with an arbitrary selected error of a few percent (locally up to 10%). Advantage of the MODTRAN 4.0 database is the high spectral resolution ($\Delta\lambda$~$1cm^{-1}$). However, the synthetic compilation database uses data from many different sources. The resulting compilations are difficult to assess, when high accurate absolute radiometric data is required. Moreover, it is unclear how irradiance variation updates (e.g. irradiance variation due to solar cycles) or improvement of the data by continues experiments (e.g. from Labs & Neckel-1962 till Neckel & Labs-1984) will be integrated in future MODTRAN versions.

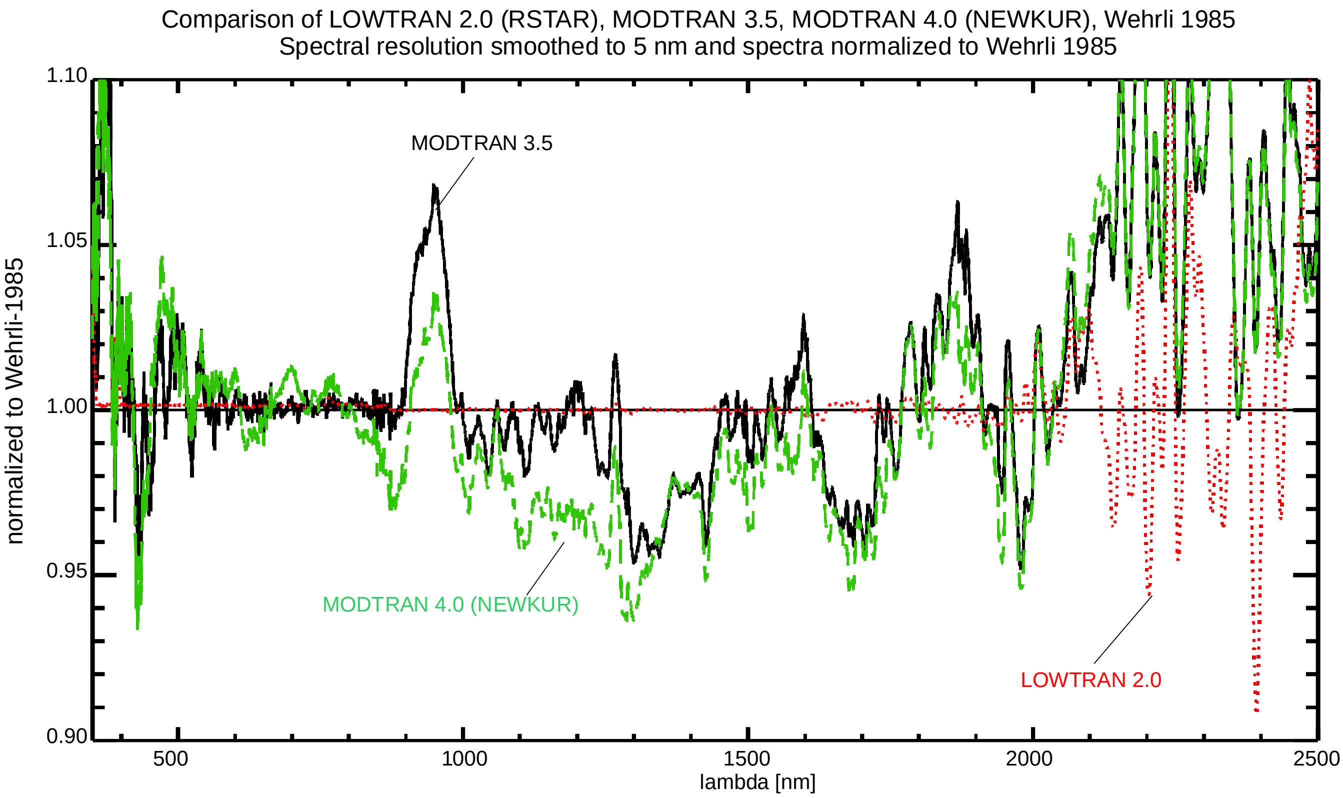

Figure 1: The solar irradiance data from LOWTRAN 2.0, MODTRAN 3.5 and the corrected Kurucz – 1995 spectrum from MODTRAN 4.0 normalized to Wehrli-1985's standard spectrum. Spectra are degraded to a spectral resolution of 5 nm.

3.2. New experiments on various space missions

In general, large parts of the solar spectrum in the VIS-SWIR are observable from the ground, however, due to atmosphere absorption (e.g. H_2O, O_2, O_3, NO_X) and scattering effects, experiments have been carried out on high-altitude observatories, balloons and aircrafts. Examples are data sets obtained at Jungfraujoch (3600 m a.s.l.) or Mauna Loa (Labs & Neckel-1962 and successive papers) or from aircraft observations in about 12 km altitude (e.g., Arvesen, et al.-1969). However, absorption still occurs and the retrieved data must be corrected for. This is why recently efforts were made to retrieve better data using space platforms measuring the absolute solar spectral irradiance in the UV, VIS and SWIR.

New experiment on various space platforms

Using space platforms various experiments were carried out recently, such as the Shuttle Solar Backscatter Ultraviolet (SSBUV), Solar Spectrum (SOLSPEC), and Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) experiments (Cebula et al.-1996) flown during the three Atmospheric Laboratory for Applications and Science (ATLAS) Space Shuttle missions conducted in March 1992, April 1993, and November 1994; also included were the SUSIM and Solar Stellar Irradiance Comparison Experiment (SOLSTICE) experiments (Woods et al.-1996), that is in operation on the Upper Atmosphere Research Satellite (UARS) since October 1991. Of these instruments, only SOLSPEC performs measurements in the spectral range above 410 nm using of three distinct spectrometers named UV, VIS, and IR. Recently, data acquired during ATLAS-1 by the UV and VIS instruments have become available in Thuillier et al.-1997 and Thuillier-1998 covering the spectral range from 200 to 876 nm. A more recent publications from Thuillier-2000 and Thuillier-2001a released refined data obtained during ATLAS mission. Additionally the IR spectrum from the EURECA mission (Aug 1992-May 1993) was taken to compile a complete spectrum from 200 nm to 2500 nm. The refinements of the Thuillier-1998 cover two spectral parts: (1) in the NIR (800-870 nm), where the uncertainty of the Thuillier-1998 data was due to the dark current increase using spectra in particular those obtained at the end of the solar observations periods when the payload was hot. To correct this Thuillier used raw data obtained in the coldest condition for the IR part of the visible spectrum. (2) over the entire Thuillier-1998 spectrum: The new compilation (Thuillier-2001a) adding ATLAS 1 and EURECA data was completed with data from Labs & Neckel 1968 to calculate the total solar energy. This integral was compared with the total solar energy at the moment of ATLAS 1 mission, what leads to an reduction of the spectra of 1.77%, what is the error budget of the data (Thuillier-2001b).

Comparison of SOLSPEC data

In the UV the SOLSPEC instruments were compared in Cebula et al.-1996 with other instruments on the ATLAS missions (UARS, SSBUV and SUSIM). Mean RMS error was in the range of 1-2%, less agreement occurred for the SUSIM comparison with >3% for shorter wavelengths. The three SOLSPEC spectra agree for the three ATLAS mission in the visible within 1.5% (mean: 1% RMS). Thuillier-2001a compared the ATLAS mission spectra with spectra obtained from high altitude observations or planes. A good agreement was found between Burlov-Vasiljev et al.-1995, Arvesen, et al.-1969 and Neckel & Labs-1984 spectra within 2-3%. However, for the Neckel & Labs below 450 nm a larger difference was found with the three missions—reaching 5 % below 400. More details are discussed in the reference. When comparing Thuillier-2001a, MODTRAN 4.0 NEWKUR, MODTRAN 3.5 and LOWTRAN 2.0 data (in Figure 2) the similarity of the discrepancy in the range from 350–869 nm becomes obvious. In this spectral region the original values from Neckel & Labs-1984 were used in the synthetic data (compare also Figure 1). The applied improvements in the MODTRAN 3.5 data lead to a reduction of the large discrepancy in the SWIR, i.e. a deviation of more than 10% between Thuillier-2001a and LOWTRAN 2.0 to less than 7% between Thuillier-2001a and MODTRAN.

Future plans

Currently, the SOLSPEC instrument is under re-configuration to take several new scientific requirements and interface specifications into account to receive a higher absolute calibration accuracy, better spectral resolution in the IR and a noise reduction (Thuillier-2000). It is planned to use this instrument on the Solar Pallet of the International Space Station (ISS) in 2004/05 (Thuillier-2001b).

Another plan is the upcoming launch of the EOS SORCE Mission which will provide long-term total solar irradiance and solar spectral irradiance measurements from 200 nm to 2000 nm at about 300 discrete wavelengths. Launch is predicted for the end of 2002. First validated data is expected to be published 2-3 month after launch (Woods et al.-2000).

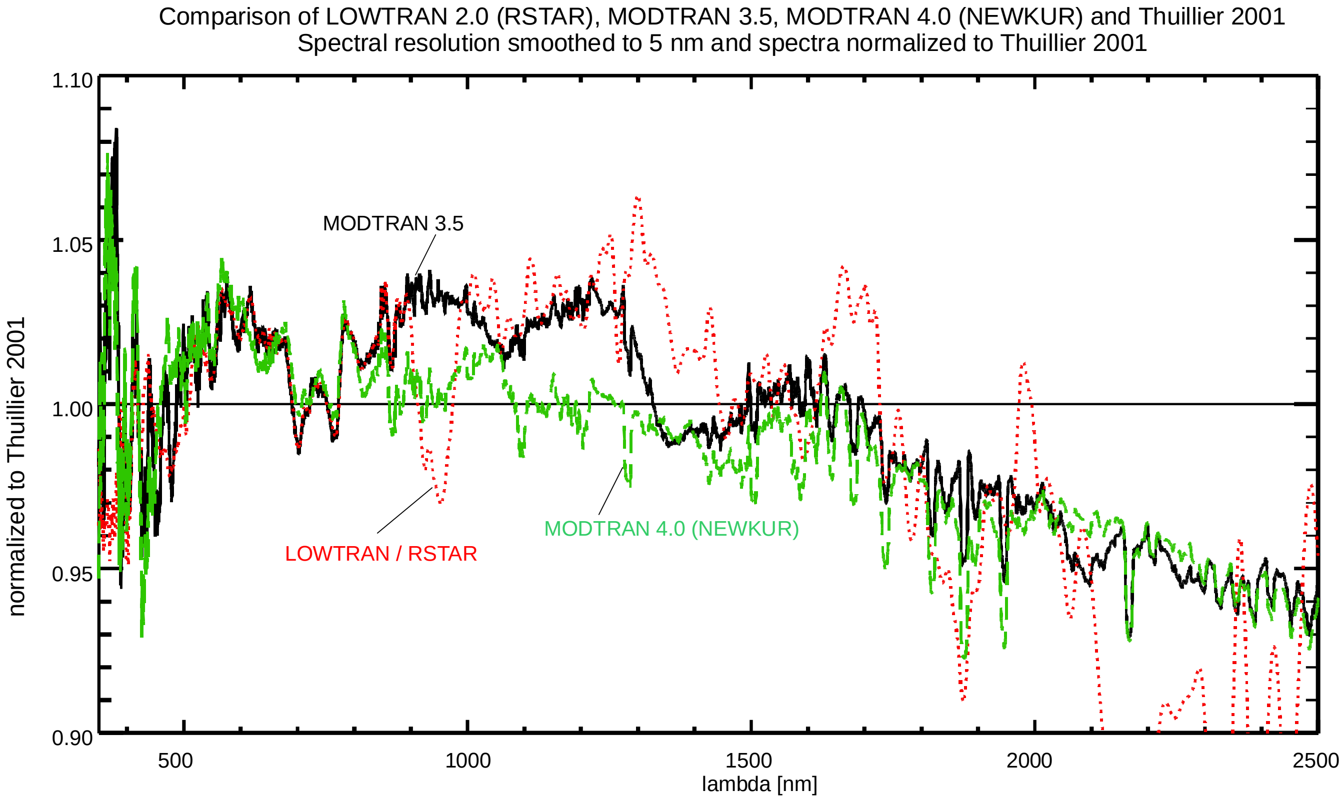

Figure 2: The solar irradiance data from LOWTRAN 2.0 and MODTRAN 3.5 and the corrected Kurucz –1995 spectrum from MODTRAN 4.0 normalized to Thuillier-2001a spectrum. Spectra are degraded to 5 nm.

Conclusion

The data retrieved by the SOLSPEC instruments on three different platforms are well-analysed solar irradiance data from 200–2500nm. Advantages of the data are the promised accuracy and the update of the data in the next solar cycle. The published error (Thuillier-2000) is < 2 % in the VIS and IR, larger errors are expected in the UV with 2-3%. Since the errors depend on the spectral interval, better values are expected in the middle of each spectral domain. The update of the experiments carried out on the solar panel of the ISS using the re-calibrated SOLSPEC instruments promises an improvement of the data accuracy. However, the data's spectral resolution is the only weak point: 1 nm (200–870nm) and 20 nm above. Nevertheless this spectral resolution is sufficient for GLI spectral bands.

3.3. A new paradigm: SOLAR-2000

Recently the idea was born to provide a new model which allows to compare various solar data sources and produces a unified data set for historical and future (forecast) data with the scientific goal to reduce the uncertainty of currently available solar irradiance data. In September 1, 2000, the Federal Data Corporation (FDC), co-operating with NOAA, released the solar irradiance model (database & software), SOLAR-2000 Research Grade v1.15 (SpaceWx-2001). This new model produces the entire solar spectrum at 1 nm resolution from the x-rays and extreme ultraviolet to the radio wavelengths taking data of various experiments (such as UARS, SOHO) into account.

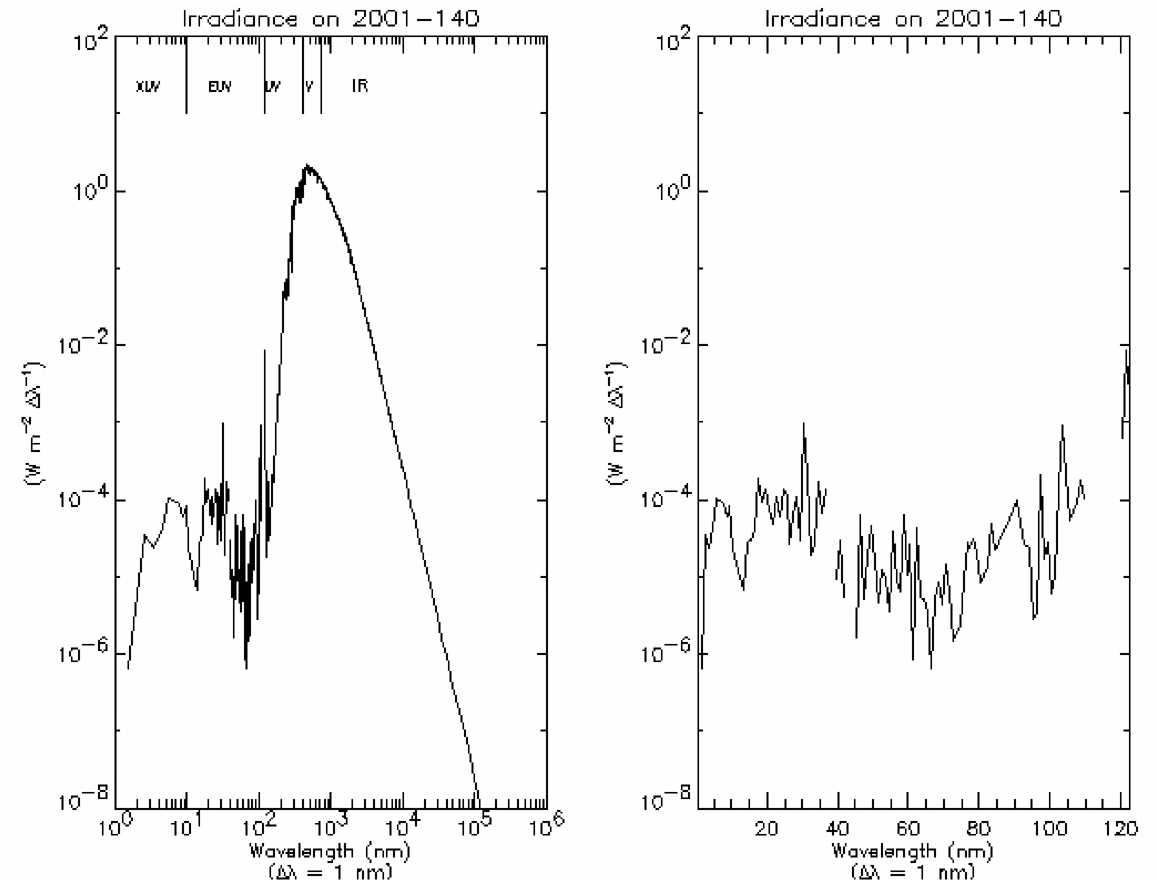

Figure 3: Example for Solar irradiation daily data: solar irradiance for 19 May 2001 (Service provided from Jan. 2001 by SpaceWX.com and NOAA). This data was published at the NOAA home page (NOAA-2001).

The SOLAR-2000 model project (Tobiska-2000) is performed in various phases with the goal to improve the accuracy of historical modelling and to provide accurate forecasts and state specifications of the solar spectrum. The forecast time-scales range from 1 hour to several years. The model is currently available as freeware to science and engineering researchers in the form of an IDL application with a graphic user interface. However, the complete implementation of the SOLAR-2000 model is currently in process. The development phases are the following: (1) model definition and design; (2) modeling of soft X-rays and extreme ultraviolet irradiance; (3) modeling of far ultraviolet irradiance; (4) modeling of UV irradiance; and (5) representation of visible, infrared, and the total solar irradiance. Finally this implementation process ensures to evolve a spectrally self-consistent empirical solar model which will meet scientific goals until 2005. Complementary information can be retrieved from Tobiska-2000.

In the initial phases the emphasis of the project belongs to the most variable part of the spectrum, i.e., the UV. The visible and infrared solar spectrum will be included in the SOLAR-2000 model by 2004. Until than the ASTM E490 (ASTM-2000) composite reference spectrum represents the VIS-SWIR part of the solar spectrum. The ASTM E490 spectrum uses Neckel & Labs-1984 values in the VIS and tabulated values from Kurucz (Kurucz-1993) in the IR (similar to the MODTRAN 3.5 data; see section 3.1). By reaching SOLAR-2000 version 4.0 (in 2004) the model will be able to represent the complete VIS-IR spectrum using new input data, such as the SOLSPEC data (Thuillier et al.-1997 and successive papers) or results from the EO SORCE mission.
Last but not least, it should be noted, that the ISO (International Standards Organization) Technical Committee 20, Sub-Committee 14, Working Group 4 (space environment, natural and artificial) is currently drafting a solar irradiance standard. The SOLAR-2000 development is compliant with the development of this standard (Tobiska-2000).

Conclusion

The SOLAR-2000 model is a promising step to reduce discrepancies between various solar irradiance data sets. It is currently focusing on the UV part of the solar spectrum. With release of version 4 (in 2004) the model will be able to provide a unique solar spectrum with an unique data quality by comparing various solar data experiments. Until then SOLAR-2000 uses the ASTM E490 to fill the VIS and IR part of the spectrum. In the VIS the Neckel & Labs-1984 data are used, and the IR values are similar to the synthetic solar spectrum from MODTRAN 3.5. Disadvantage is the lack of error estimation in the references (ASTM-2000) and no update of the actual VIS-data until release of SOLAR-2000 version 4.0 in 2004.

4. Calculation of uncertainties using GLI’s response functions

There are two main methods to compare high spectral resolution spectra: One is to degrade the spectral resolution of the spectra (e.g. to 5-6 nm) and calculate the ratios of the spectra (as applied in Figure 1 and Figure 2). The other method is to compare the spectra by integrating the spectrum and the sensor’s response functions over the wavelength between the minimum and maximum spectral response levels of the channel. The ration of the integrated values help to compare the irradiance sources.
For the GLI project it is advisable to use the spectral response function method, which has the advantage of determining the exact deviation for each of the GLI channels.

Selected solar irradiance data sets

It is apparent that there are numerous other solar spectrum data sets available. Figure 4 gives an overview and origin of commonly used data sets (for description see also section 3). This figure makes evident, that the work published in Neckel & Labs 1984 and Smith & Gottlieb 1974 delivered the fundament for the many compilations and modifications of solar spectrum data, such as Wehrli-1985, LOWTRAN and MODTRAN and SOLAR-2000. In contrast to the Neckel & Labs 1984 and Smith & Gottlieb 1974 data, which were achieved using ground based observatories, observations on space platforms were carried out recently. Results were published in Thuillier et al. and successive papers. (Note, that D. Labs was involved in the calibration of the SOLSPEC instruments.) Further SOLSPEC experiments will be carried out in future to perform solar observations from an ISS platform.

For calculation of the GLI's in-band solar irradiance the following basic experiment solar irradiance data was selected: Thuillier-2001a (200–2500 nm), Neckel & Labs-1984 (330–1245nm) and Smith & Gottlieb-1974 data. Additionally, the MODIS-2000 data set was chosen, because it is a newer compilation version using Thuillier-1996, Neckel & Labs-1984; Smith & Gottlieb-1974 data. And finally the solar data from LOWTRAN 2.0 RSTAR, MODTRAN 3.5 and MODTRAN 4.0 NEWKUR were used for the in-band solar irradiance calculation.

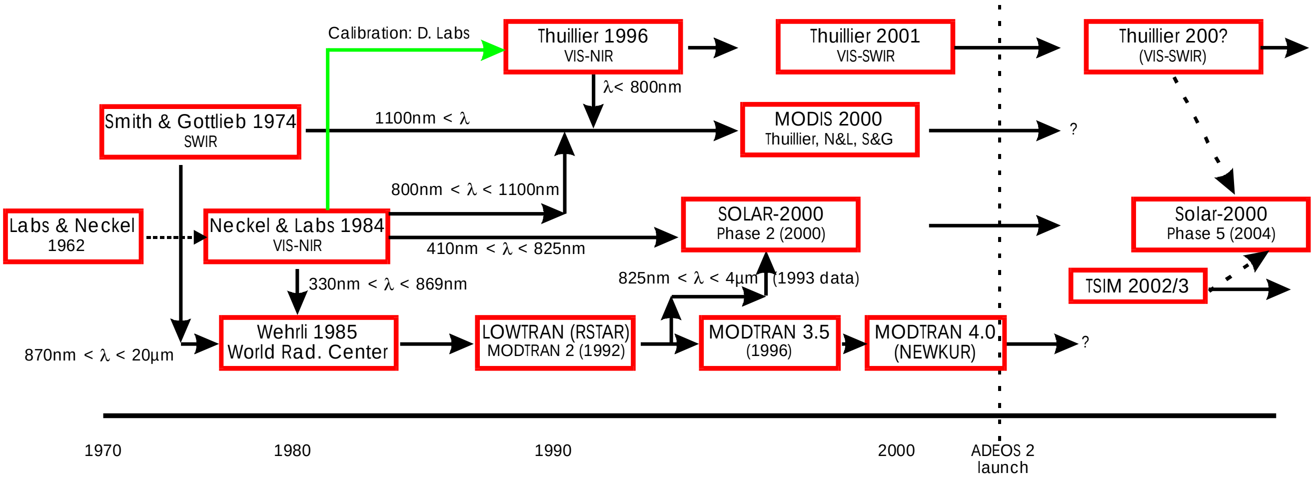

Figure 4: Commonly used solar reference spectra in the VIS-SWIR

GLI response functions and the solar reference spectra

In the following the GLI response functions and the solar reference data are plotted over the UV–SWIR wavelength. The spectral sections were separated into the UV-VIS (350-600nm), the VIS-NIR (600-1000nm) and the SWIR (1000-2500nm). The solar reference data were interpolated to a spectral sample width of $\Delta\lambda$ = 0.2nm. As response function the latest GLI values (Murakami-2001) were taken. An overview of the spectral characteristics of each of GLI's reflective channels can be depicted from Figure 8.

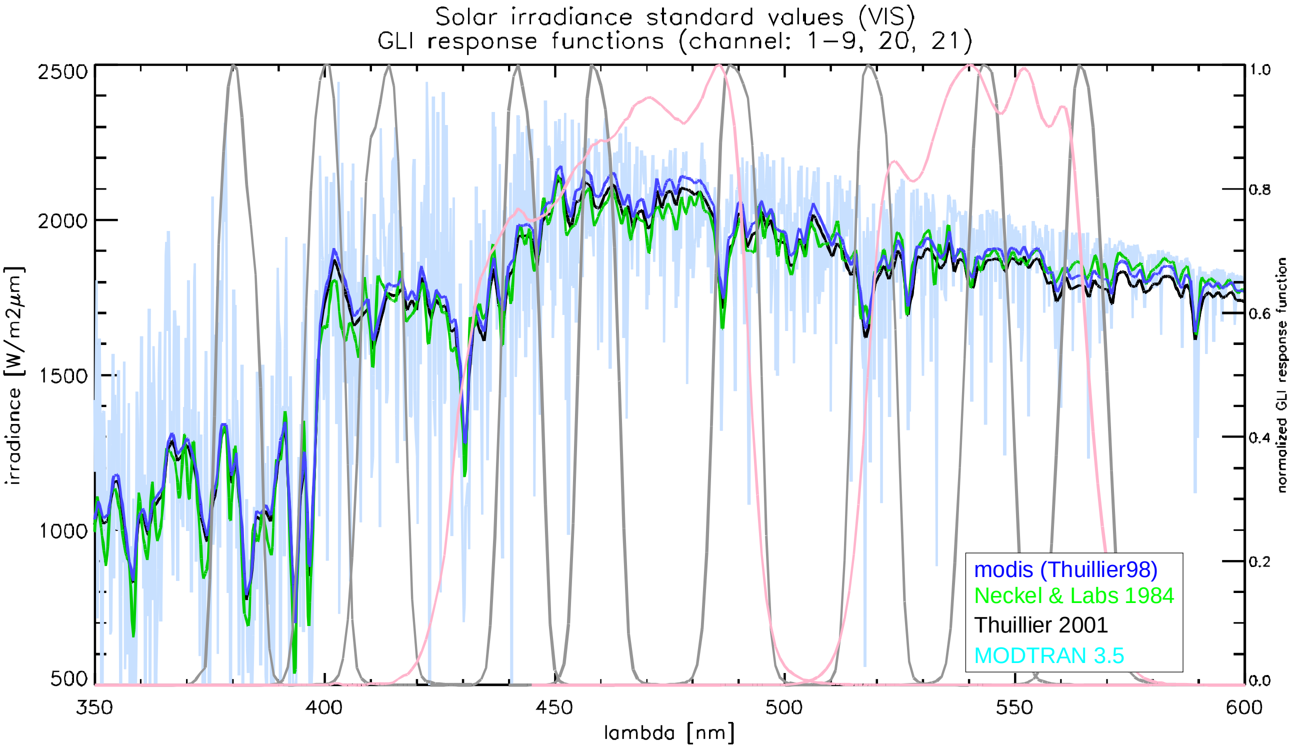

Figure 5: GLI channel 1-9 and 20, 21 in the UV-VIS part of the solar spectrum

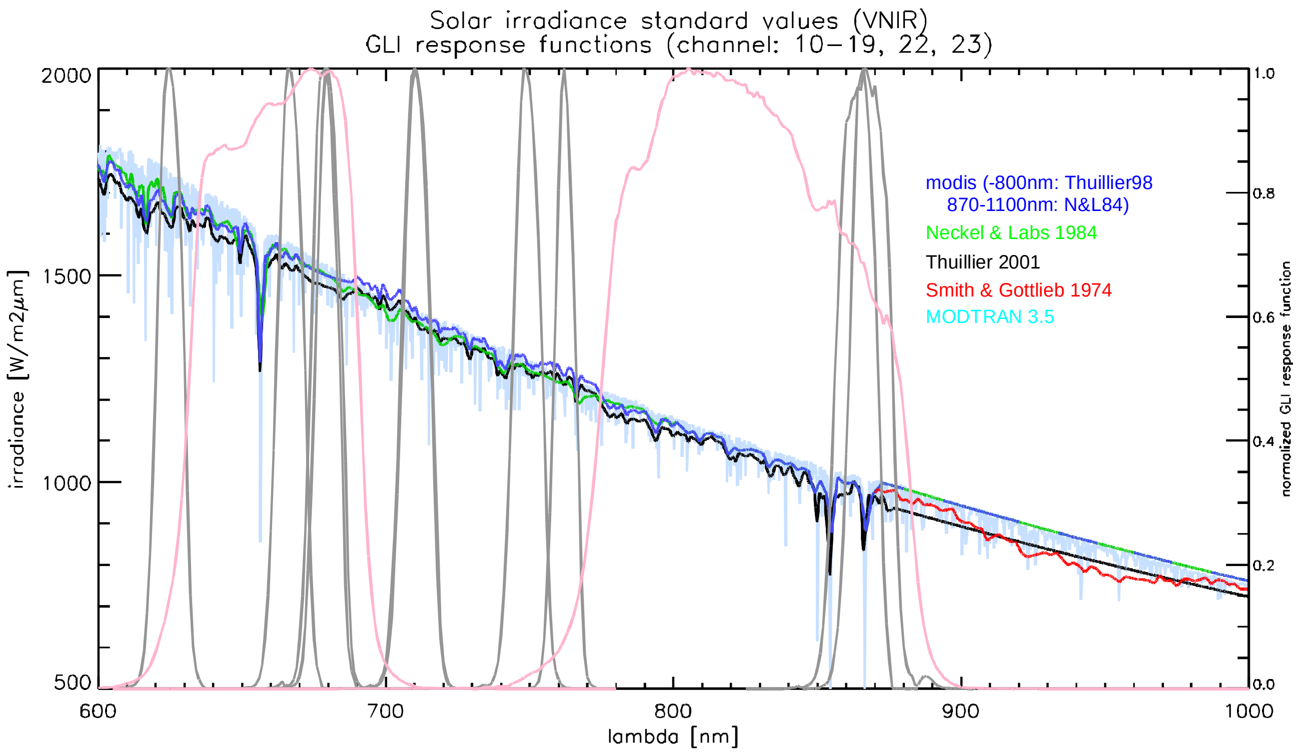

Figure 6: GLI channel 10-19 and 22, 23 in the VIS and NIR part of the solar spectrum

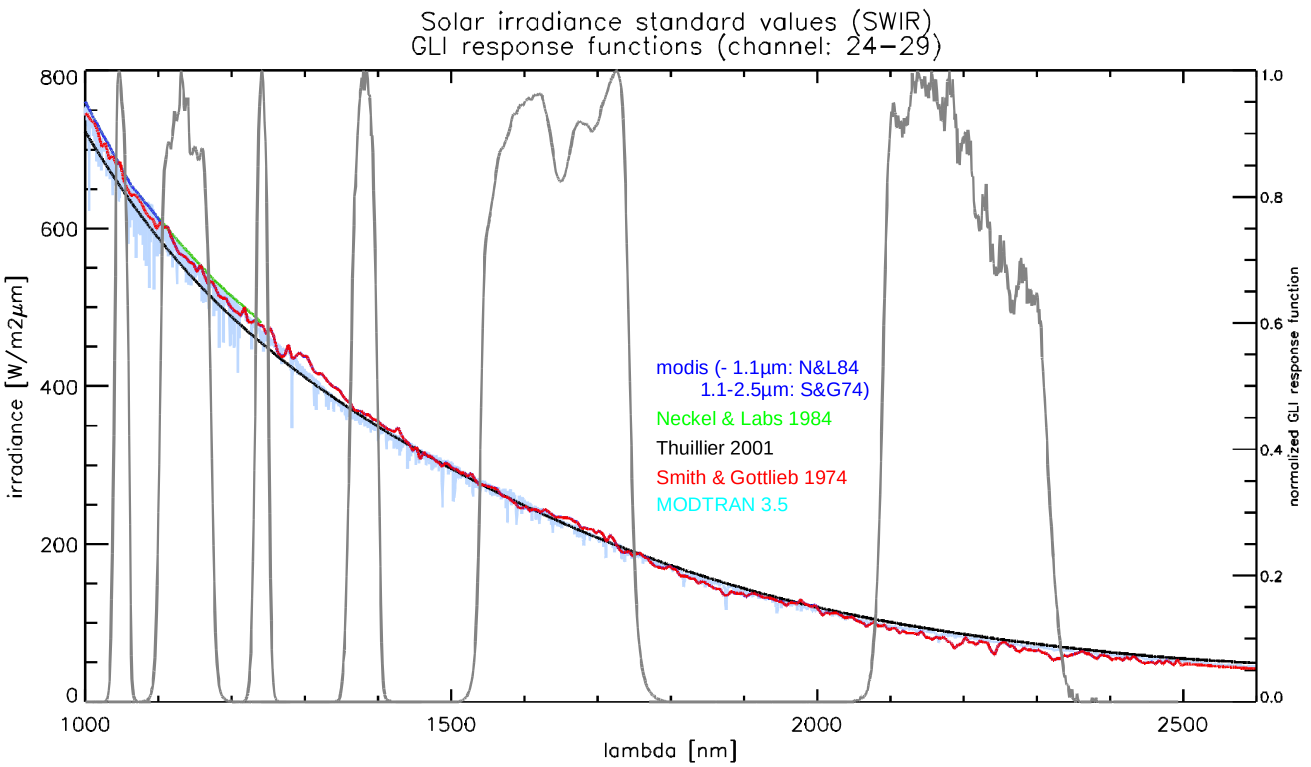

Figure 7: GLI channel 24-29 in the SWIR part of the solar spectrum

Figure 5 (UV-VIS) shows the plot of Thuillier-2001a, Neckel & Labs-1984, MODIS-2000 (here: Thuillier-1998) and MODTRAN 3.5. As expected, the deviation of the plots is larger in the UV and smaller in the VIS, where the maximum solar irradiance is located. Note, that Thuillier corrected the Thuillier-1998 data for 1–1.7% (Thuillier-2001b). Thus, the Thuillier-2001a curve is shifted to smaller irradiance values.

The VIS-NIR spectral region is presented in Figure 6. Whereas Thuillier-2001 and Neckel&Labs-1984 data have small discrepancies in the VIS part, some significant differences are observable in the NIR: Around 940 nm the Neckel & Labs data have the highest values. The Thuillier-2001a,b values are parallel shifted to lower irradiance values (about 5%). The Smith & Gottlieb data are placed between those curves having the shape of an absorption curve at 940 nm. This phenomena has been pointed out by Goa-1995. They found that this spectrum contains absorption features which are not of solar origin but the result of atmospheric water vapour absorption. The flatness of the Thuillier-2001a and Neckel & Labs-1984 curves is due to the spectral resolution of the original data, which stays in contrast to the high resolution MODTRAN data. However, it becomes apparent, that the number of absorption lines significantly decrease with longer wavelengths and that an high spectral resolution spectra is not needed for GLI's broad spectral bands.

The SWIR spectrum range is plotted in Figure 7. Here the Neckel & Labs 1984 data are only reported until 1.25 µm. Note, that Goa-1995 reported for the Smith & Gottlieb data the possible occurrence of absorption lines, that are not of solar origin: the Earth atmospheric oxygen band at 1.268 µm and many absorption features in the 2.0–2.5-mm region. Hence, the Smith & Gottlieb data became difficult to access.

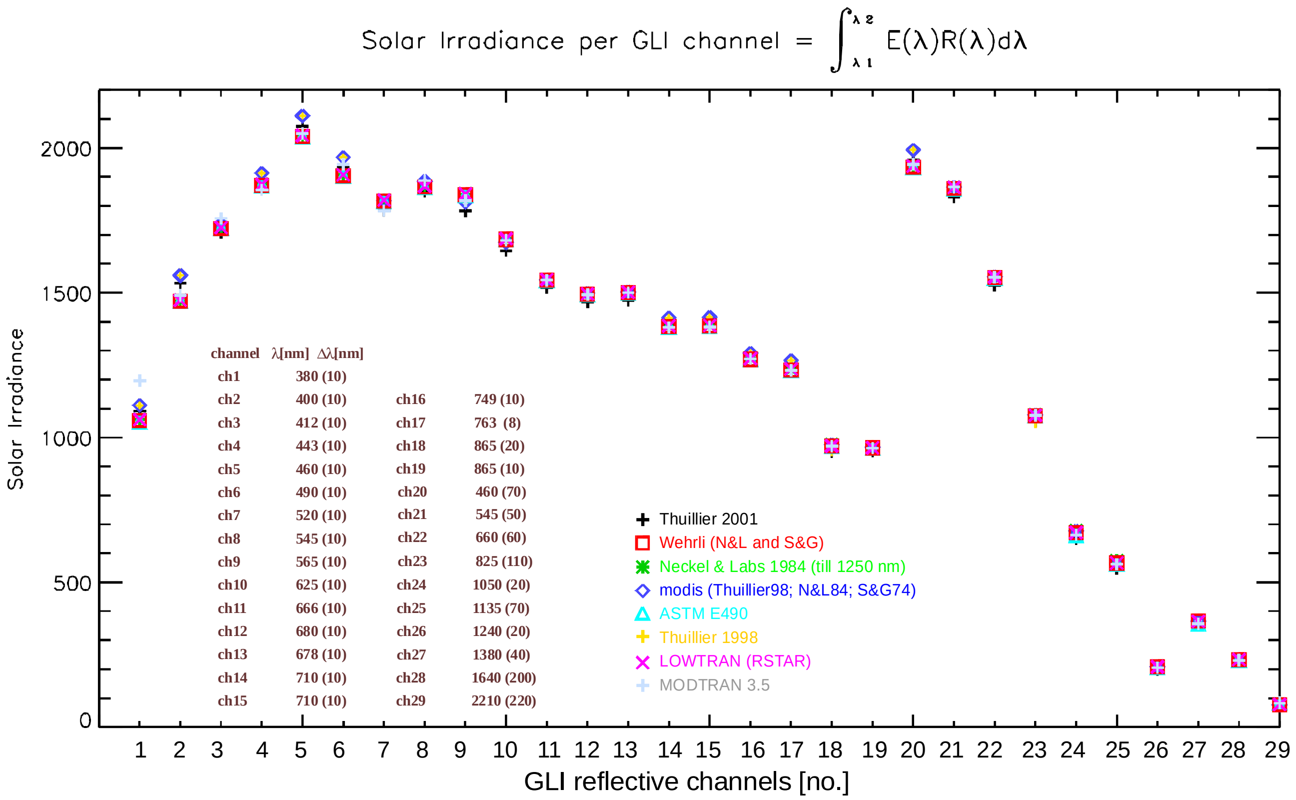

Figure 8: Solar irradiance weighted by GLI's response functions for all reflective bands of GLI

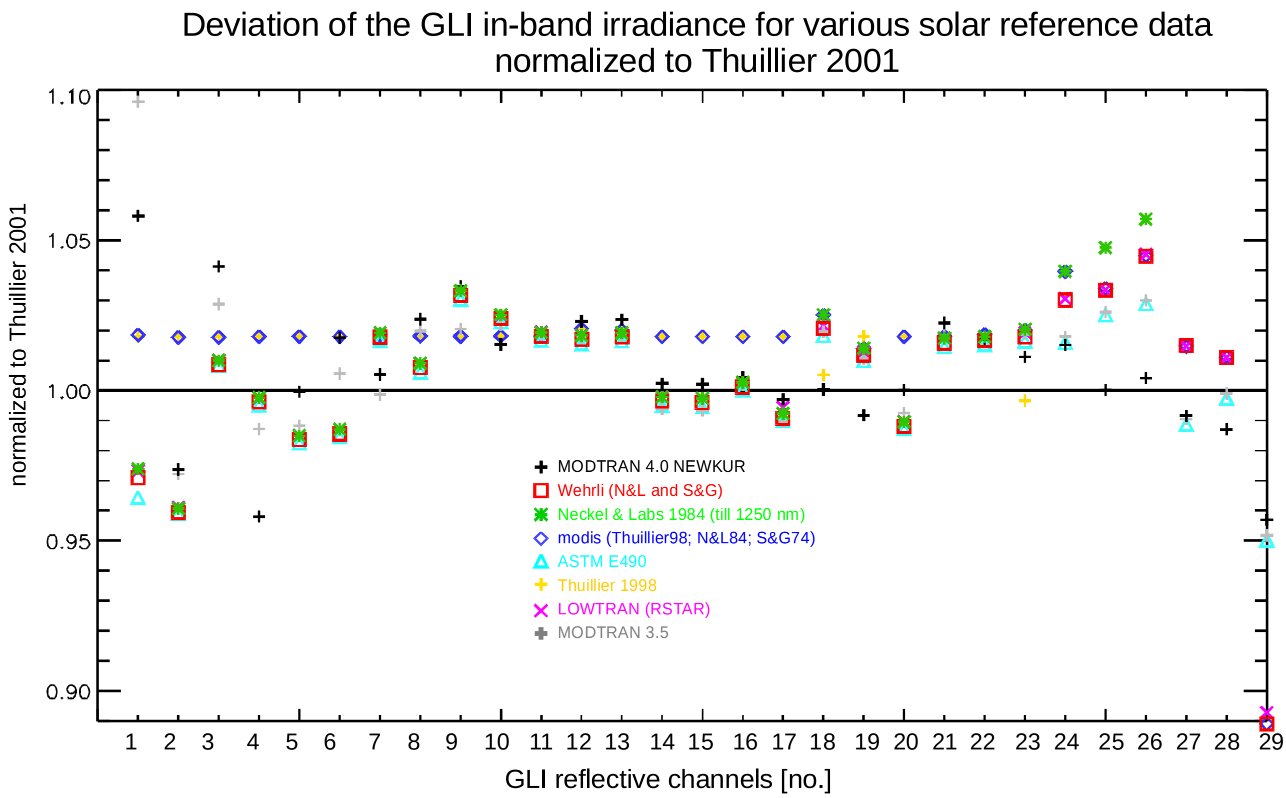

Figure 9: Deviation of the integrated values from Figure 8 normalized to Thuillier 2001a data

The integrated values are plotted for GLI's 29 reflective channels in Figure 8. The solar data from Thuillier-2001a, Thuillier-1998, Neckel & Labs-1984, MODIS (compilation of Thuillier-1998, Neckel & Labs-1984, Smith & Gottlieb-1974), Wehrli-1985 (compilation of Neckel & Labs-1984, Smith & Gottlieb-1974), ASTM, LOWTRAN 2.0 and MODTRAN 3.5 were weighted by the response functions of the GLI channels. In the range from channel 1 to 19, the resulting values follow the shape of the E0 values. Channel 20-23 have broader spectral resolution in the VIS-NIR and channels 24-29 are placed in the NIR and SWIR region of the solar spectrum where the solar irradiance values become very small.

Figure 9 represents the data—plotted in Figure 8—normalized to Thuillier-2001a,b values. It becomes obvious, that for channel 1–17 and 21–23 the Wehrli-1985 and Neckel & Labs in-band irradiance fluctuate only by a small factor. This factor was used by Wehrli to scale the complete spectrum to the solar constant values (see section 3.1). The larger difference between Thuillier-1998 (UV-NIR) and Thuillier-2001a are due to a refinement of the SOLSPEC data (see section 3.2).

In the VIS-NIR (channel 3 – 23) the deviation is in the range of 2-3%, what is congruent with the published error estimations. In the UV and SWIR the deviation is larger, due to lack of comparison data, uncertainties in the instrument calibration etc. The deviation exceeds about 5% for the channel 1 and 2 in the UV and the channels 24-26 in the SWIR. (Note, that the difference to the MODTRAN 3.5 data can be explained with the high oscillations reported in Schmid et al.-1998). However, the results for channel 27, 28 and 29 are a bit of surprise: Whereas the channels 27-28 match very well (about 2%) , the deviation to Thuillier-2001a data in channel 29 is quite large: 11% with LOWTRAN 2.0 and Smith & Gottlieb-1974 and 5% with ASTM and MODTRAN 3.5 and MODTRAN 4.0 NEWKUR. This large deviation might be the result of uncertainties in the original Smith & Gottlieb data (compare with Goa-1995), uncertainties in the calibration of the instruments and the low spectral resolution of the Thuillier-2000 data ($\Delta\lambda$ = 20nm). However, considering the efforts made in the recent 20 years in the field of spectrometer calibration, it seems quite reasonable to believe in the Thuillier-2001a data.

5. Conclusion

The decision of proper selection of solar irradiance data for the GLI mission is driven by the following factors: (1) suitability in terms of spectral coverage and resolution, (2) reliability in terms of small estimated errors underlined by comparison measurements and (3) expected updates (improvements) of the data in near future. However, to avoid recalculation of the look-up tables during the GLI mission, there is the operational request to select only a single spectrum for the entire mission. This is why a significant change in the solar irradiance values will only result in an update of the GLI calibration coefficients error estimation.

The SOLAR-2000 model (Tobiska-2000) promises to be a reliable absolute solar irradiance data source for the future. The SOLAR-2000 model is able to reduce discrepancies between various solar irradiance data sets by comparing these data with different other solar experiments such as results from the SOHO mission. Moreover, the progress of SOLAR-2000 model is compliant with the development of the International Standards Organization (ISO) solar irradiance. However, the SOLAR-2000 project is currently focusing on the X-UV and E-UV part of the solar spectrum. With release of version 4 (in 2004) the model will be able to provide a unique solar spectrum with a unique data quality by comparing various solar data experiments. Until 2004, SOLAR-2000 uses the ASTM E490 to fill the VIS and IR part of the spectrum. Unfortunately, the ASTM values are a compilation of Neckel & Labs data (Neckel-1984) and a synthetic solar spectrum from Kurucz-1993, which seems to need an update/improvement for the next solar cycle. Another disadvantage of the ASTM data is the lack of error estimation in the reference.

Without doubt, the most recent versions of solar irradiance data available in MODTRAN 4.0 database are a good sources for synthetic solar irradiance data. Main advantage of this database is the high spectral resolution (up to $\Delta\lambda$~1cm^{-1}). However, the synthetic compilation database uses data from many different sources. The resulting compilations are difficult to assess, when high accurate absolute radiometric data is required. Moreover, it is unclear how irradiance variation updates (e.g. irradiance variation due to solar cycles) or improvement of the data by continues experiments (e.g. from Labs & Neckel-1962 till Neckel & Labs-1984) will be integrated in future MODTRAN versions.

In section 3.2 it was outlined, that there are new experiments (Thuillier-2000, Woods et al.-2000) on various space platforms which promise the desired update of the former standards by overcoming the problem of possible atmospheric absorption features in the data and by providing updates for the next solar cycle. One of the promising candidate is the SOLSPEC instrument (200–2500nm), which is currently re-calibrated and in preparation for new experiments on the solar panel of the ISS. This instrument has been used on various other space experiments (Thuillier-1998), hence the data is well-compared and has an estimated error (Thuillier-2000) of less than 2 % in the VIS and IR, and about 3% in the UV (up to 350 nm). Another candidate is the EO-SORCE (Woods et al.-2000). One of the objectives of the mission is to perform solar irradiance measurements in the range from 200-2000nm continuously for the envisioned mission duration of 5 years. Until final validation of the SORCE data in 2003, the Thuillier data seems to be the best choice, regarding the above mentioned selection criteria. Without question, from 2003 it becomes even more difficult to assess the different (e.g. SOLSPEC, TSIM) data sources. That is why the SOLAR-2000 model should be used with release of version 4.0 in 2004.

Hence, the following strategy seems to be promising in selecting the most reliable source for extraterrestrial solar irradiance:

1. Selection of the Thuillier-2001 (SOLSPEC measurements from 350 to 2500nm; Thuillier-2001a),
2. From 2004, selecting the SOLAR-2000 model version 4.0 as a primary source for solar irradiance data (Tobiska-2000).

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