The SOLSPEC Experiment: Recent Results and Future Investigations on Board the International Space Station Alpha

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Abstract. The SOLSPEC investigation has already been flown in orbit for measuring the absolute solar spectral irradiance. The scientific objectives for the ISSA mission are presented and their importance is discussed. The performance of the instrument will be shown using the recent SOLSPEC results. For the ISSA mission, changes have been already undertaken in order to meet the ISSA requirements (interfaces and reliability) and several instrumental improvements for a better science return.

SCIENTIFIC RATIONAL AND OBJECTIVES

We are developing an instrument to measure the solar spectrum irradiance from 180 to 3000 nm on board the Space Station. The aims of this investigation are the study of the solar variability at short and long term during the next solar cycle 23 and the achievement of absolute measurements (2 % in UV and 1 % above). These measurements are important for the photochemistry of the stratosphere minor constituents, Earth's Climatology and Solar Physics. It is considered to fully refurbish the SOLSPEC instrument to meet the Space Station requirements and to improve its performance after the experience gained in the past missions.

Scientific rational

Two decades of measurements of both total and spectral solar irradiance have definitively shown the variability of the solar output. This can be extended also to particles flux. These data have revealed changes on time scales from minutes to decades. Previous observations using the sunspots and ^{14}C data showed longer periodicities such as the Gleissberg and Suess cycles of 90 and 200 years respectively. Ideally, for purpose of Solar Physics, Climatology and Atmospheric Physics, the knowledge of the Sun output would be required over these time scales. This has not been achieved obviously and it represents severe difficulties in organizing such an observational program. This is why, the use of solar proxies is important to characterize the solar output at a given time. The most used proxy is the F10.7 cm radio flux, but the Mg II index seems very promising for the UV domain.

The solar variability affects in principle the whole electromagnetic spectrum, but at different rates according to wavelength. Below 300 nm, the variability increases as the wavelength decreases. Along the 11-year solar cycle, the solar irradiance changes by 8% at 200 nm, but may reach one order of magnitude at shorter wavelength. The lowest variability is met in the visible and near infrared domains. However, within some Fraunhofer lines variability induced by the solar rotation (27-day) and the 11-year solar cycle has been detected (e.g. the Ca H and K lines at 393 and 396 nm). In the radio domain, variability is recorded on a daily basis.

For the Solar Physics, the whole spectrum is important. For the Atmospheric Physics, the solar photons of wavelengths shorter than 450 nm are involved in many key reactions with the Earth's atmosphere chemical species. Reactions are typically photodissociation, photoabsorption and photoionization occurring in the upper atmosphere. Photochemical reactions with ozone and nitrogen dioxide are catalytic reactions which require the knowledge of the solar irradiance with great accuracy (Nicolet, 1981). The atmosphere thermal structure depends

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on the absorption of solar photons by certain constituents. This is illustrated by the temperature increase of the stratosphere due to the absorption of solar photons by ozone and in the lower thermosphere by atomic oxygen.

Consequently, the solar irradiance below 450 nm is important for the study of the Earth's atmospheric composition and temperature due to photodissociation, photoabsorption and photoionization processes which are wavelength dependent.

The total solar irradiance (the solar constant) concerns at the first order the Earth's Climatology. However, the albedo of ground and clouds is also wavelength dependent as are the absorptions by the minor constituents.

Solar Physics, Climatology and Atmospheric Physics are then concerned by accurate measurements of the solar spectral irradiance. However, the Sun variability is a function of wavelength which induces composition and temperature changes with time. The corresponding variability has been identified in the stratosphere, mesosphere and thermosphere. Solar variability is also evoked concerning climatic changes (Withbroe and Kalkofen, 1993).

Below 330 nm, the measurements are obtained from balloons, rockets, satellites and Space Shuttle to avoid the very important absorptions mainly due to ozone. The early measurements presented significant differences when comparisons were made between data sets. Accuracy of standards, procedures of absolute calibration and instruments aging were considered as possible causes of discrepancies. Today, the differences between standards are significantly reduced (smaller than 1% in the visible and 2% at 250 nm, (Köhler et al., 1996)) and procedures of absolute calibration are now well defined and reliable. As for aging, its causes are now identified and solutions were found allowing to reduce as much as possible its effect on the absolute solar irradiance measurements.

A review of the data sets obtained during the 80's is given in our last papers (Thuillier et al., 1997, 1998a and b). For the 90's, the measurements were regularly carried out by the Upper Atmosphere Research satellite and the ATLAS (ATmospheric Laboratory for Applications and Science) missions. UARS launched in 1991 and still operating, carries two spectrometers observing from 120 to 410 nm (SUSIM, Brueckner et al., 1993 and SOLSTICE (SOLar STellar Irradiance Comparison Experiment) spectrometers, Rottmann et al., 1993)

The Mg II index is characterized by the depth of that line with respect to the solar continuum (Heath and Schlesinger, 1986). It allows to infer the solar variability as a function of wavelength. It is more and more used in Atmospheric Physics. These measurements started with NIMBUS 7, were performed with few interruptions by the same type of instrument (SBUV) on board the NOAA spacecrafts series.

The ATLAS missions operated in March 1992, April 1993 and November 1994, a payload dedicated to Atmospheric and Solar observations. The last one consisted in SUSIM, SSBUV and SOLSPEC instruments. The need for long series of measurements was acknowledged, but the ATLAS missions stopped after ATLAS 3. As UARS launched in 1991 may stop some time, it is important to continue. The Space Station capabilities fulfill the requirements to carry out solar measurements.

When comparing the strategy of the 80's and the 90's, it appears that missions combine one or several of the following aspects:

- recalibration after flight when instruments could be retrieved,
- comparison of data gathered either from instruments placed on the same platform or placed on different platforms but operated at the same time
- development of reliable in flight calibration lamps
- intercomparison of instruments before flight

This has certainly contributed to the good agreement between solar irradiance measurements. Detailed comparisons were made by Cebula et al., 1996 and Thuillier et al., 1997 and 1998b for the domain 200-350 nm observed by the SSBUV, SUSIM and SOLSPEC instruments. The RMS differences are of the order of 2 to 3%. Larger differences may exist nearby strong Fraunhofer lines as expected due to the different instruments slit function. Similar conclusions are obtained with the UARS data as shown by Woods et al., 1996.

The visible part of the solar spectrum is observable on the ground. However, atmospheric absorptions mainly due to ozone, nitrogen compounds, and water vapor are still acting, and infer corrections. The highest altitude measurements are, the smallest are the corrections. This is why high altitudes observatories, balloons and airplanes are used. The data sets covering the visible domain were obtained either on the ground (Neckel and Labs, 1984; Burlov-Vasiljev, 1995) or from planes (Arvesen et al., 1969; Lockwood, 1992) and, from orbit by the SOLSPEC instrument. Comparisons of these data were made by Thuillier et al., 1998a and 1998b. Discrepancies are observed nearby strong Fraunhofer lines and especially below 450 nm where measurements are the most corrected. The best agreement between SOLSPEC (ATLAS missions) and other data sets was found with the Burlov-Vasiljev' data and Neckel and Labs' spectrum (above 450 nm) within 2 to 3%.

SOLSPEC-ISSA Objectives

For measurements carried out on the ground, the correction of the atmospheric absorptions is certainly the most important source of errors. From orbit, no corrections are needed, but other sources of errors exist due to the space environment and the aging of the optical elements due to the short wavelength photons (EUV and XUV) and particles. This is why an adequate sampling of the solar irradiance, an instrument incorporating internal sources and post-flight calibrations are important to achieve accurate measurements.

The SOLSPEC scientific objectives are:
- determination of the solar spectral irradiance from 180 to 3000 nm with an accuracy of 2% in UV and 1% above.
- determination of the solar variability in that wavelength domain and determination of the Mg II index.
- achievement of correlative measurements with other solar instruments observing the Sun (total solar irradiance and EUV domain) as presently foreseen.

These measurements in the domain 180-3000 nm are related to the Earth's Atmospheric Physics, its Climatology and Solar Physics. The three solar instruments placed on the Space Station will benefit of a strong synergy because the Sun output will be covered from the EUV to the infrared domain representing 99% of the total solar irradiance which will be also measured at the same time.

The SOLSPEC instrument will be calibrated with several means. The synchrotron radiation and blackbody will be the two primary standards and lamps will be used as secondary standards (deuterium and tungsten ribbon lamps). For the mission foreseen on board the Space Station, we plan to calibrate SOLSPEC in the absolute scale provided by NIST (National Institute for Standards and Technologies), NPL (National Physical Laboratory) and PTB (Physikalisch-Technische Bundesanstalt). Figure 1 shows an example of spectrum measured by the SOLSPEC instrument.

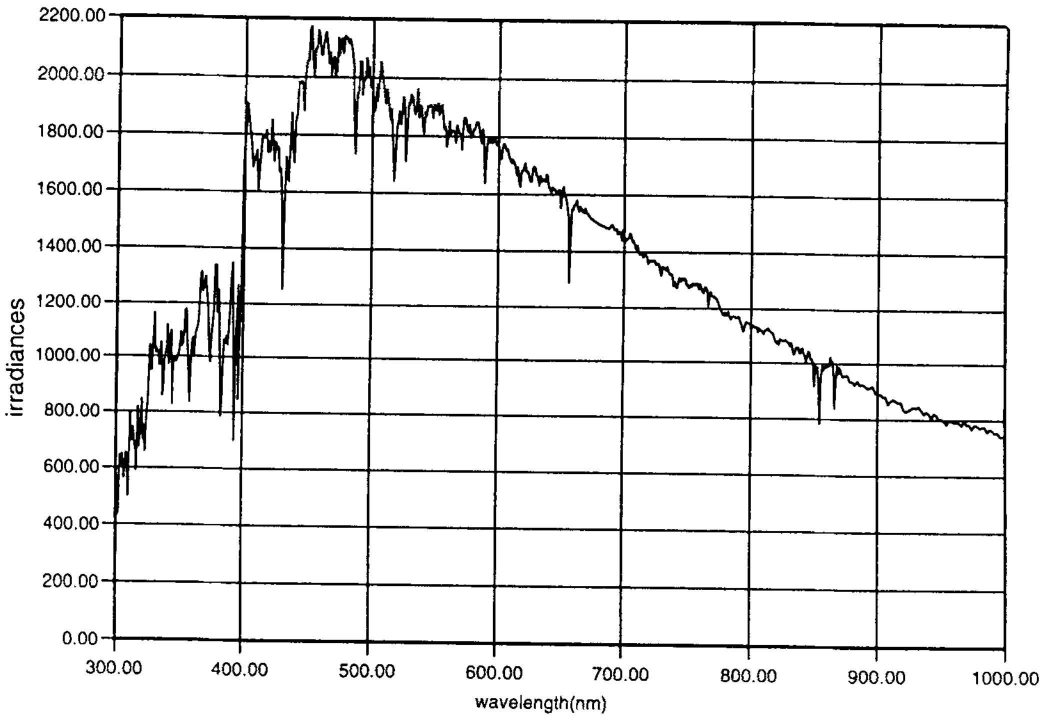

FIGURE 1 . Solar spectrum from 300 to 1000 nm measured by the SOLSPEC instrument during the ATLAS I mission. Solar Irradiances are given in $mWm^{-2}\ nm^{-1}$

INSTRUMENT

The SOLSPEC experiment has been described in our last papers. The data processing of the space data has shown the areas where improvements can be made. Consequently, we foresee to fly a similar instrument which takes into acount the following changes:

a) the on board calibration
The WINDII experiment flown on board the UARS satellite carried a tungsten ribbon lamp. The lamp was operated one hour per week during 7 years in orbit. The stability of the responsivity over that duration was found to be better than five percents (Thuillier et al., 1997). This changes was mostly due to the thermal environment change inducing a filament temperature change. Consequently, monitoring the lamp temperature allows to reduce its drift as we foresee to do for the present design. On board the same spacecraft, the SUSIM experiment dedicated to the solar irradiance measurements between 120 and 410 nm used a deuterium lamp. The SUSIM data gathered in orbit have shown a lamp stability compatible with our scientific objectives. Furthermore, it is space designed. Two tungsten and two deuterium lamps will be placed in the instrument for redundancy and comparisons.

b) we anticipate a long duration flight. Aging is a key aspect of this investigation due to its direct impact on the final accuracy of the measurements. Most of the aging is induced by the EUV radiations which are outside of our domain of observations. A quartz plate in front the entrance slit is able to absorb most of the damaging radiations. A wheel placed in front of each spectrometer entrance will carry three plates and one hole. This arrangement allows to observe the Sun either directly or through the plates which transmission can be measured using the internal lamps. A typical scenario consists in using the plates at different frequency.

c) a Sun sensor will be incorporated within the instrument to allow small responsivity corrections as a function of the Sun position in the field of view.

d) the microprocessor will achieve all sequences of measurements previously used during the ATLAS missions plus some others providing flexibility for ground and space observations such as for the determination of the Mg II index.

e) the cooling of the visible detector will be improved in order to reduce the systematic errors due to the detector dark current which become not negligible typically at both extremities of the visible spectrometer spectral domain.

f) the infrared spectrometer will benefit of a low noise electronics and an improvement of the spectral resolution from 20 to 4 nm.

The following description takes into account these improvements. The instrument is made of three spectrometers to cover the wavelength domain which extends from 180 nm to 3000 nm. Each spectrometer consists in a double monochromator using holographic gratings. This optical arrangement reduces the scattered light. The gratings are fixed on a common mechanical shaft which rotates by steps being driven by a nut-screw and a stepper motor. It allows a wavelength positioning of the order of 0.01 nm. The detectors in the UV and visible domains, are photomultiplier tubes. A PbS cell is used in the infrared. At each spectrometer exit slit, a wheel carries second order filters and appropriate attenuators to maintain the number of counts in the linear range. The wheels have several positions, two in UV, four in visible and three in infrared domains. They rotate as a function of wavelength according to the solar irradiance and the spectrometer's responsivity. Diffusers are placed in front of each spectrometer entrance slit to achieve an uniform illumination of the first grating and to reduce the effect of depointing during the observations. The bandwidths of the UV, visible and infrared spectrometers are 1 nm, 1 nm and 4 nm respectively. The spectral sampling corresponds to about 0.4 nm, 1 nm and 4 nm for UV, visible and infrared channels respectively. The responsivity and the spectral characteristics of the spectrometers are checked by use of calibration lamps placed in the instrument. A copper hollow cathode lamp filled with He provides about 20 emission lines allowing to monitor the wavelength scale and the instrument bandpass on the ground and in orbit in both UV and visible domain. Table 1 summarizes the instrument characteritics.

TABLE 1 : SOLSPEC-ISSA spectrometers characteristics

Spectrometer	UV	VIS	IR
Spectral range	180 - 360 nm	340 - 850 nm	800 - 3000 nm
Grating manufacturer	Jobin-Yvon	Jobin-Yvon	Jobin-Yvon
diameter	30 mm	30 mm	30 mm
ruled area diam.	28 mm	17 mm	17 mm
ruling frequency	3600/mm	1281 /mm	354 / mm
curvature radius	96.3 mm	100 mm	87.4 mm
focal length	99.42	99.42	99.42
bandpass at	200 nm : 1.45 nm	389 nm : 1.4 nm	1000 nm : 3.8 nm
	360 nm : 1.17 nm	707 nm : 1.2 nm	3000 nm : 4.2 nm
increment per step	0.4 nm	1 nm	4 nm
plates (nb)	Suprasil (3)	Suprasil (2)	Infrasil (2)
entrance window	Suprasil I	Suprasil I	Infrasil
surface (mm^2)	0.4 x 1	0.16 x 1	1 x 1
dectector	PMT	PMT	PbS cell
type	EMR G 641 F	EMR 641 E	OTC-22S-8
window	MgF_2 (solar blind)	glass 9741	Infrasil
photocathode	CsTe	Trialkali	photocathode
cooling	no	T= -20°C	T=-15°C

The SOLSPEC instrument was built in two identical units. The first flew with the SpaceLab1 mission. It was fully refurbished for the ATLAS missions and was operated three times in space. The second unit made solar observations during 8 months on board the EURECA platform. For these five flights, no problem was encountered.

However, for the ISSA mission, a new unit will be prepared using the actual spectrometers, but microprocessor, motors, lamps, and all other subsystems (power supplies, Peltier cooling, ...) will be new. The housing of the instrument will be designed to accommodate the ISSA interface requirements. Space qualification tests will be performed before integration on the solar pallet. To operate in orbit, the instrument requires 50 W. Its mass is 28 kg and its dimensions are 44*44*43 cm. The telemetry rate is 1 kbits per second. The instrument needs to be pointed toward the sun. It is able to accommodate a depointing up to 3 arc degrees. However, the best results are obtained with a pointing better than 1 arc degree. The investigation requires a minimum of 12 minutes of uninterrupted solar observations per day. Daily internal calibration may be operated in any attitude. The instrument retrieval allowing recalibration after operations in orbit, is fundamental for this investigation.

The participating institutes to the SOLSPEC-ISSA investigation are: Service d'Aéronomie du CNRS (France), Institut d'Aéronomie Spatiale (Belgium), Landessternwarte of Heidelberg (Germany), National Physical Laboratory (UK), Naval Research Laboratory (US), and World Radiation Center (SW).

CONCLUSION

We plan to observe the solar spectrum from 180 to 3000 nm on board the Space Station. The aims of this investigation are:

i) the study of the solar variability at short and long term during the next solar cycle,

ii) the achievement of absolute measurements (2 % in UV and 1 % above)
iii) the determination of the Mg II index
iv) the study of topics relevant of the synergy with the other instruments placed on the same platform.
These measurements are important for the photochemistry of the atmosphere minor constituents, the Earth's Climatology and Solar Physics.

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