



Solar Metrology, September 21-23 2015



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The Solar Spectral Irradiance in the Near IR

Review and discussions on the available measurements and associated uncertainties

- Scientific rationale
- Available data sets and instruments
- Presentation of ground-based measurements
- Discussions on the SOLSPEC measurements



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- The photosphere (top of the convective zone)
- ~300 km of thickness, negative gradient (T°)
- SSI variability (wavelength, amplitude, periodicity)
- Variability below 0.05 % in the NIR
- Quiet Sun: photospheric continuum (~6000 K)

The opacity of the photosphere in the NIR

- Radiative processes associated to H^-
→ continuous absorption, optical density

Bound-free transition: $H^- + h\nu \rightarrow H + e^-$

Cross section: maximum at 0.85 μm , zero above 1.65 μm

Free-free transitions: $H^- + e^- + h\nu \rightarrow H^- + e^-$

(inverse of the bremsstrahlung radiation)

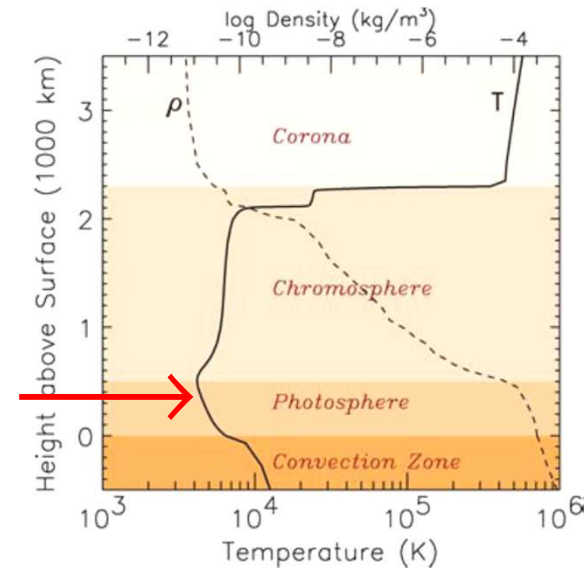
Cross section: increasing with wavelength

- Total opacity of the Sun and solar-type stars:

- Local maximum at 0.85 μm
- Minimum at 1.65 μm
- New increase > 1.65 μm

SSI NIR measurements

→ probing the T° profile of the photosphere





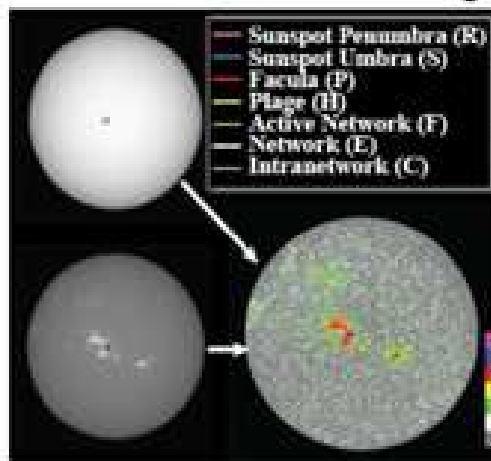
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Semi-empirical modeling

- The objective is to reproduce the SSI (absolute scale), the TSI and their variability). Combination of:
- Encoded fundamental physical processes
(emissions & radiative transfers occurring in the solar atmosphere)
 - Sun imagery for the solar activity
 - SSI measurement from space for the validation (adjusting parameters for constancy between modeling & observations)

Example:

- Modeling from Fontenla (SRPM, FAL 93 99 02...)
developed from VAL81 (Vernazza et al., 1981)



*NIR Validation with inputs from SORCE
(Fontenla et al., 2004) and ATLAS 3
(Fontenla et al., 2006)*

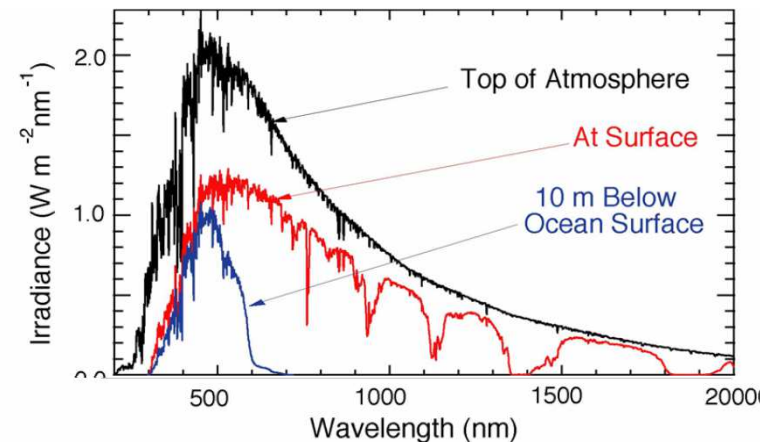
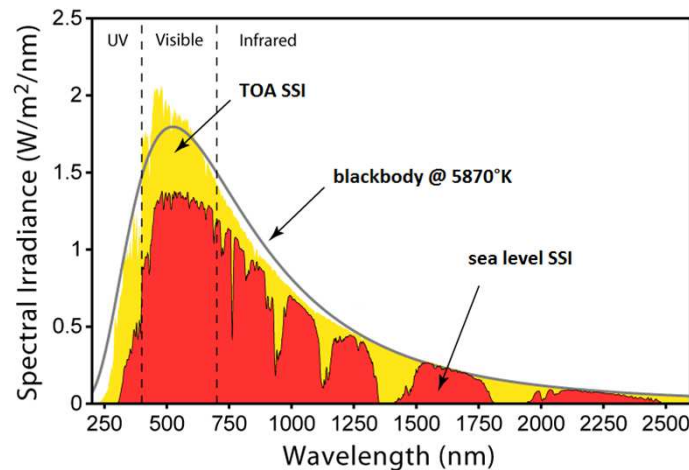
- Modeling from COSI (S. Shapiro, Haberreiter et al.)



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The Solar Spectral Irradiance in the Near IR

TOA SSI from 700 nm to 2400 nm
→ ~1/2 TSI



- Absorption by the atmosphere (CO_2 , H_2O , O_3 , O_2) & upper layer of the oceans
→ role in the Earth's radiative budget
- NIR SSI measurements are of prime importance for the validation of semi-empirical modeling of the solar atmosphere, for radiative transfer and climate research.
- Relative paucity of available TOA SSI NIR set of data
(SIM on SORCE, SOLSPEC, SCIAMACHY, data from Arvesen, Neckel & Labs)



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- Before the first space measurements:
 - High altitude: Labs & Neckel 1962, revised until 1984
 - From airplanes: Arvesen, Griffin, and Pearson (1969) and Thekaekara (1974), *Uncertainties of 3 % in the NIR*
 - Composite spectra, by assembling several segments Colina, Bohlin, and Castelli (1996)

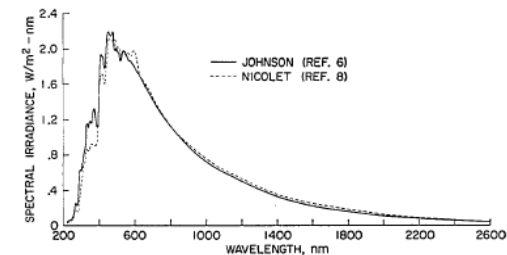
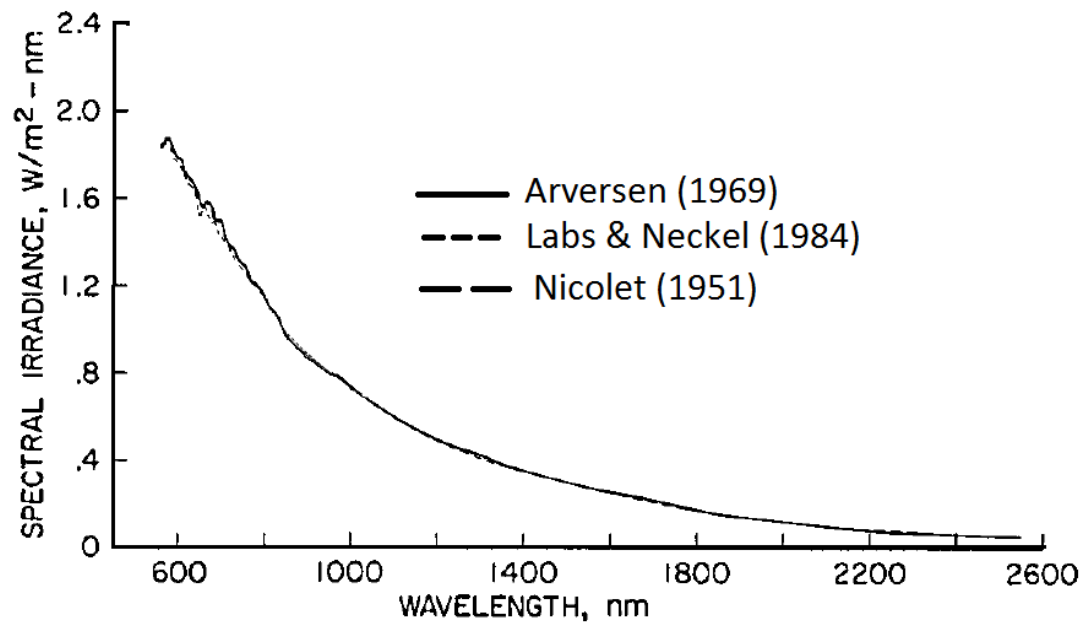


Fig. 1. Comparison of solar spectral irradiance, Johnson and Nicolet.

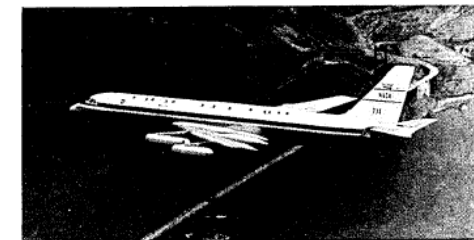


Fig. 2. NASA CV-990 jet aircraft showing upper and side observation windows.



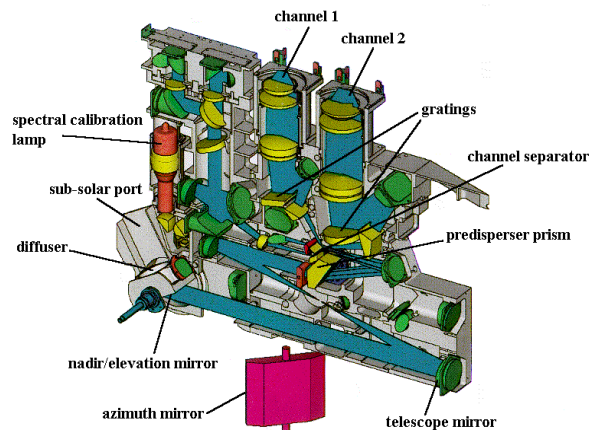
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From space: 1) Sciamachy (ENVISAT)

8 channels (CCD). Designed for remote sensing.

Absolute calibration, SSI capabilities up to $2.4 \mu\text{m}$. 2002-2012

SCIAMACHY Instrument Design



2) SIM on SORCE

Prism spectrometer, twin channels, characterized,
absolute calibrated detector (bolometer)

→ Since 2003, measurements up to $2.4 \mu\text{m}$. Normalization on ATLAS 3



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SOLSPEC – double monochromators, concave gratings, PbS detector, absolute calibrated (blackbody)

SpaceLab-ATLAS-EURECA missions (first version of SOLSPEC)

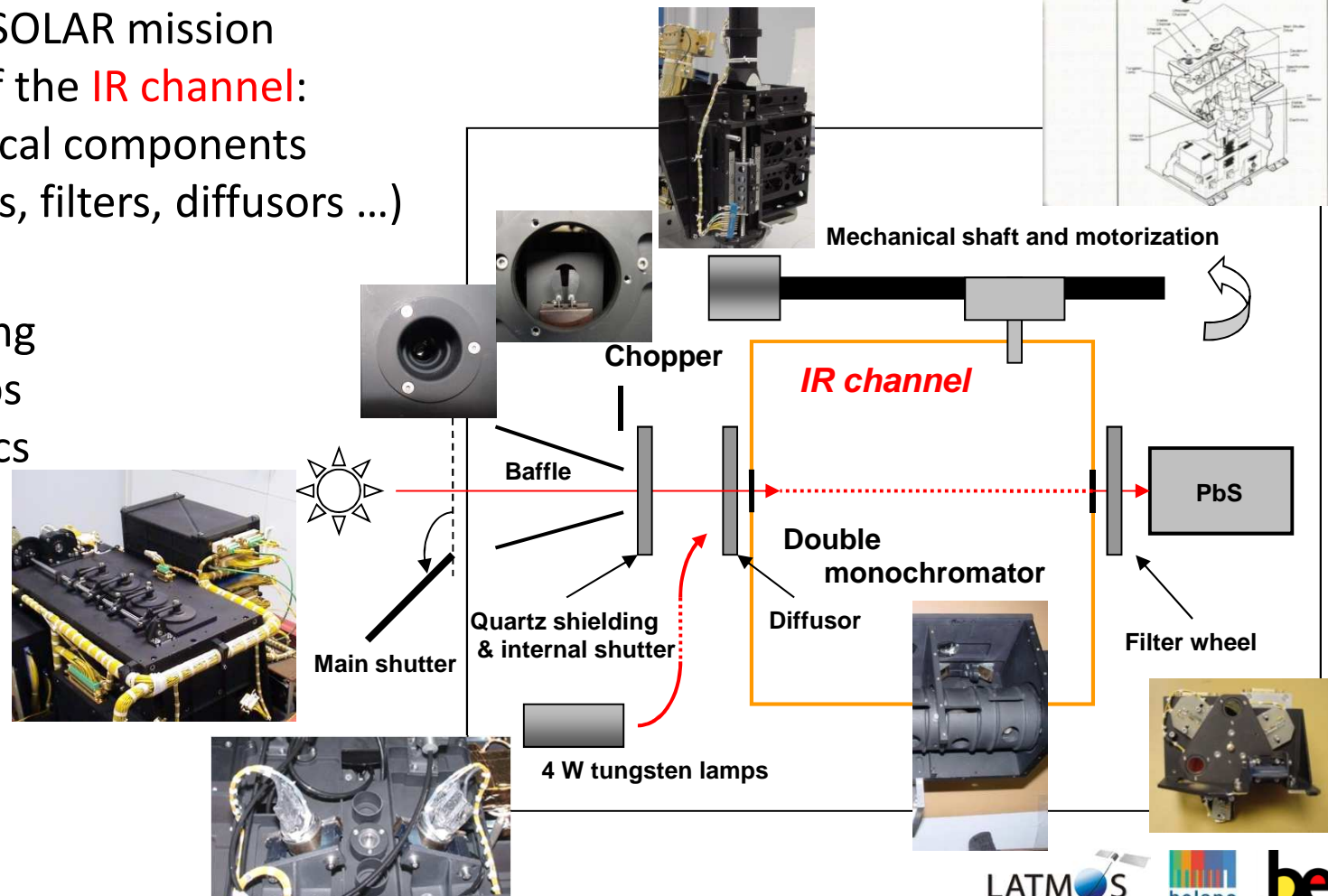
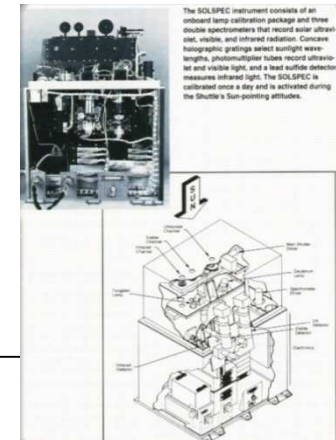
For the SOLAR mission

Refurbishment of the **IR channel**:

- Renewed optical components (gratings, filters, diffusors ...)

New items:

- Quartz shielding
- Tungsten lamps
- New electronics





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The IRESPERAD ground-based measurements (BIRA-IASB, 2011)

This work is published in Solar Physics since 17th January 2014

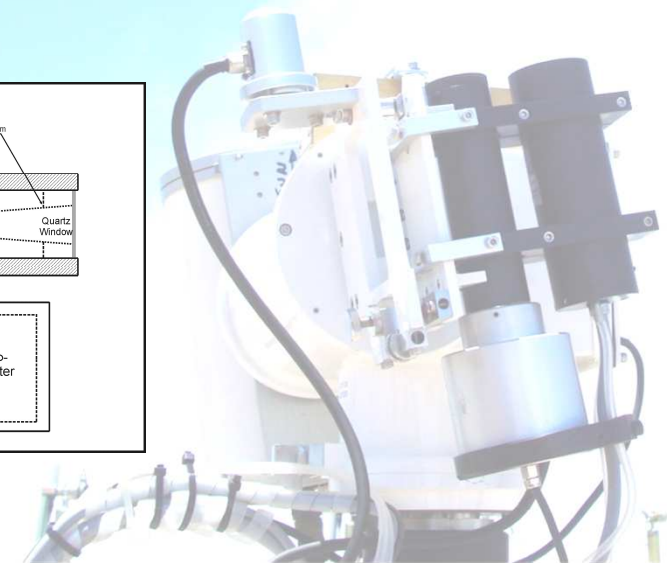
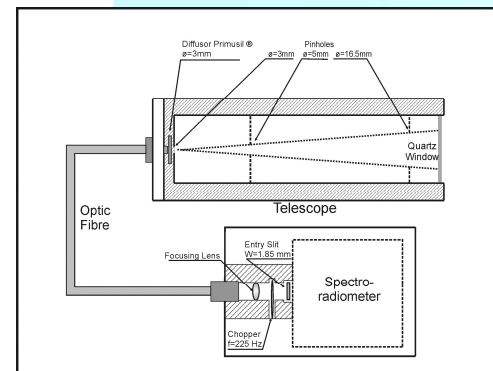
→ online version DOI 10.1007/s11207-014-0474-1

→ Ground-based measurements performed through few atmospheric NIR windows.

→ TOA SSI values extrapolated using the Bouguer–Langley technique.

Using:

- High performance instrument
- Accurate absolute calibration
- High altitude site



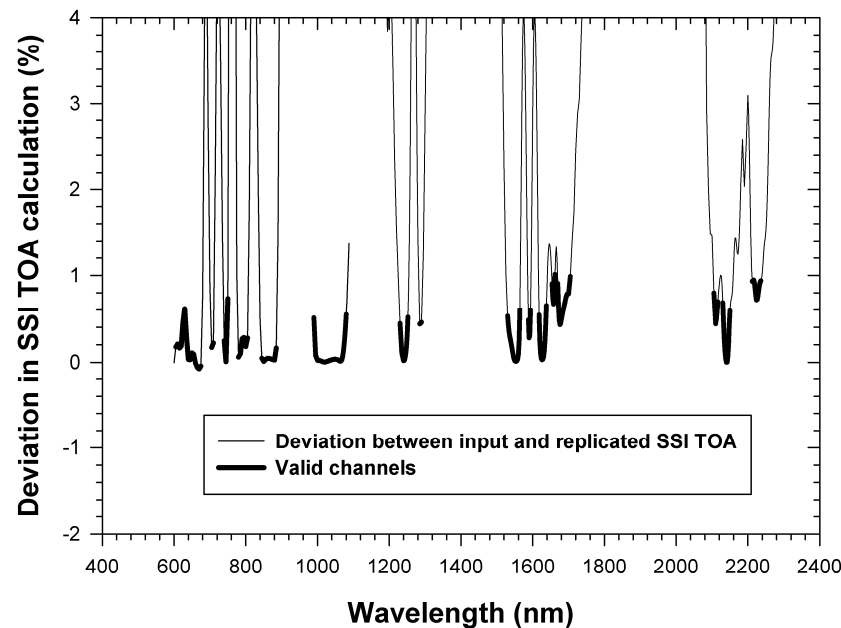
Uncertainty estimation using the LPU



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→ Bouguer-Langley method using WTLS algorithm

$$\log(E(\lambda)) = \log(E_0(\lambda)R^{-2}) - m(\theta)\tau(\lambda)$$



$E_0(\lambda)R^{-2} \rightarrow$ TOA SSI at 1 UA

$E(\lambda) \rightarrow$ ground-based SSI

$\theta =$ Solar zenith angle

$\tau =$ optical depth

AMF (m) between 2 and 8

→ Atmospheric windows (164 channels)

Method: *Kindel et al., Appl. Opt,*

2001, pp 3483-3494

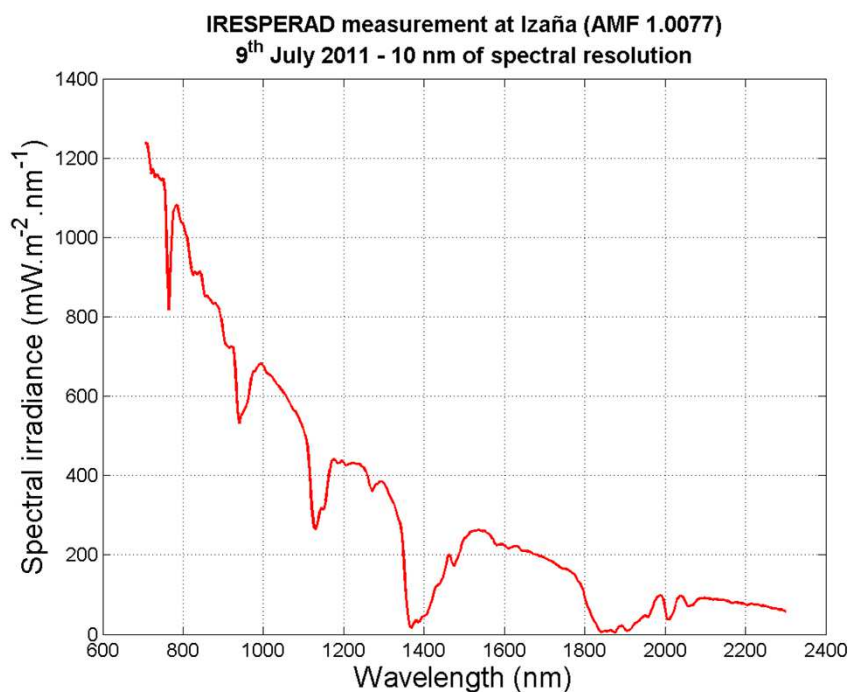
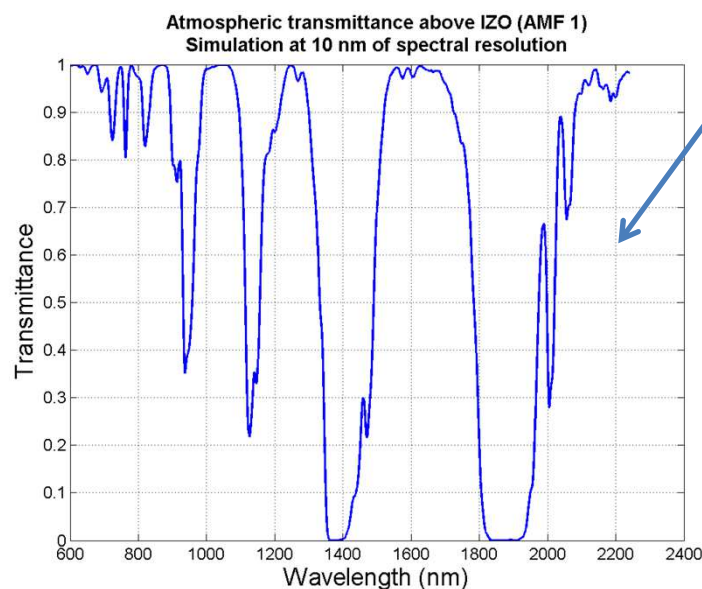


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Atmospheric windows (absorption free regions)

→ Atmospheric transmittance ($FWHM$ 10 nm) above IZO (from modelling)

Absorption from all species: H_2O , O_2 , CO_2 , CH_4 , N_2O , CO , NO_2 , O_3 , O_4



→ Real SSI measurement (IRESPERAD) at IZO (9th July 2011), AMF 1.0077



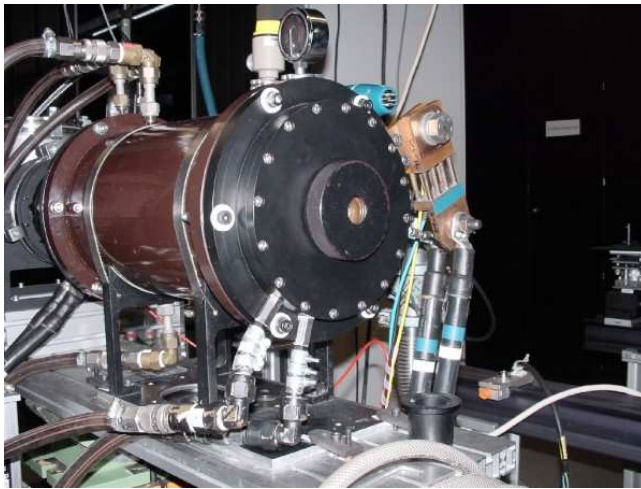
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IRSPERAD

Absolute calibration & radiometric characterization

Blackbody radiator BB3200pg of the PTB, as used for SOLAR/SOLSPEC

→ primary standard for dissemination of spectral irradiance



Cavity Temperature : 2890 K

Uncertainty = 0.44 K

Drift < 0.1 K/h

10 times more stable than the blackbody (Heidelberg) used for ATLAS 3

- IRSPERAD *relative calibration*
→ Four 1000 W NIST FEL lamps
- IRSPERAD *characterization*
→ λ scale, thermal behavior, ...



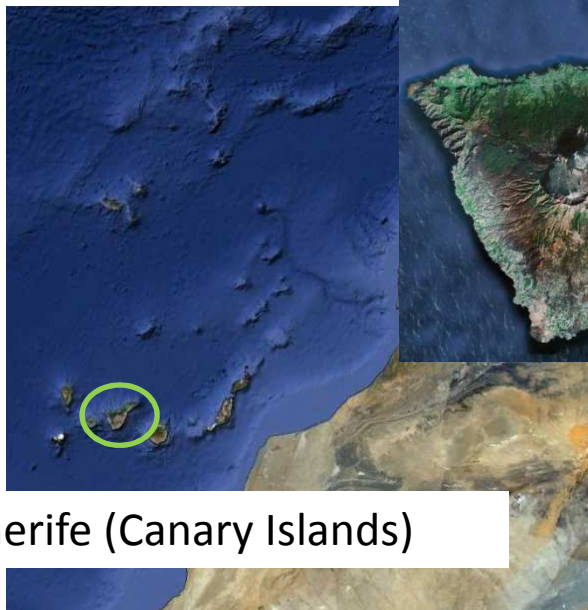
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Measurement site → High-mountain Izaña Observatory (IZO)

The site

→ Managed by the Izaña Atmospheric Research Centre (IARC),
from the State Meteorological Agency of Spain (AEMET)



Tenerife (Canary Islands)



28°3'N, 16°5'W

2367 m asl

Insolation ~ 3400 h/year



- IZO is part of the GAW Precision Filter Radiometer (PFR) network,
managed by the World Radiation Centre (Davos, Switzerland)
- IZO hosts the reference triad of the WMO-GAW Regional Brewer
Calibration Centre for Europe (RBCC-E)
- IZO is a direct-Sun calibration site of AErosol RObotic NETwork (AERONET)



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The site

High-mountain Izaña Observatory (IZO)

Stability of atmospheric conditions, no anthropogenic disturbances

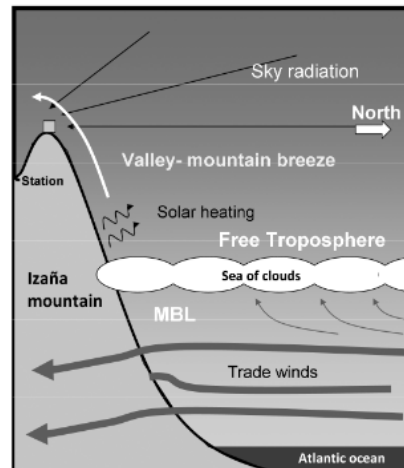


Fig. 1. Schematic view of the Izaña station from the East face. The sea of clouds drifts between 800 m in summer months to 1500 m in winter months.



Puenteadura, O. et al., . *Atmos. Chem. Phys.* **12**, 4909 – 4921, 2012

- IZO is above the quasi-permanent strong temperature inversion and so free of local anthropogenic influences. The inversion separates the moist marine boundary layer from the dry troposphere.
- IZO is favoured by a large scale high stability subsidence flow regime
→ Large number of clear-sky days per year

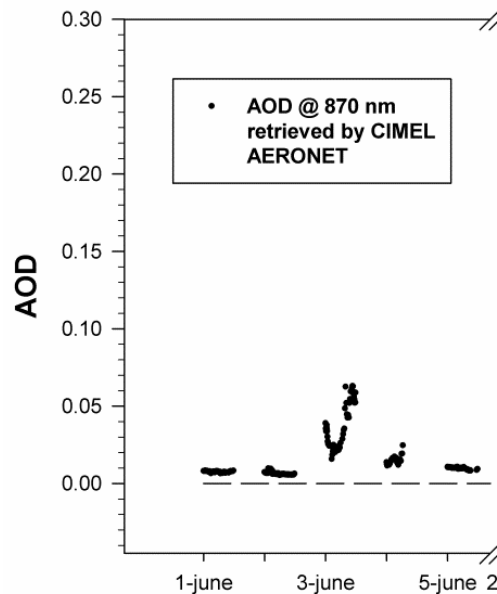


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Applying the Bouguer-Langley law at IZO

“... mountain tops like Mauna Loa in Hawaii or Izaña in Tenerife provide environments where the constancy of the optical depth is frequently assured...these results [Langley plots] are rarely controversial.” [Kiedron & Michalsky, 2015]

“... the error effects imposed by the atmosphere, even for surface (high altitude mountains) observations can be reduces below the one percent level if care is taken.” [Shaw 1975]

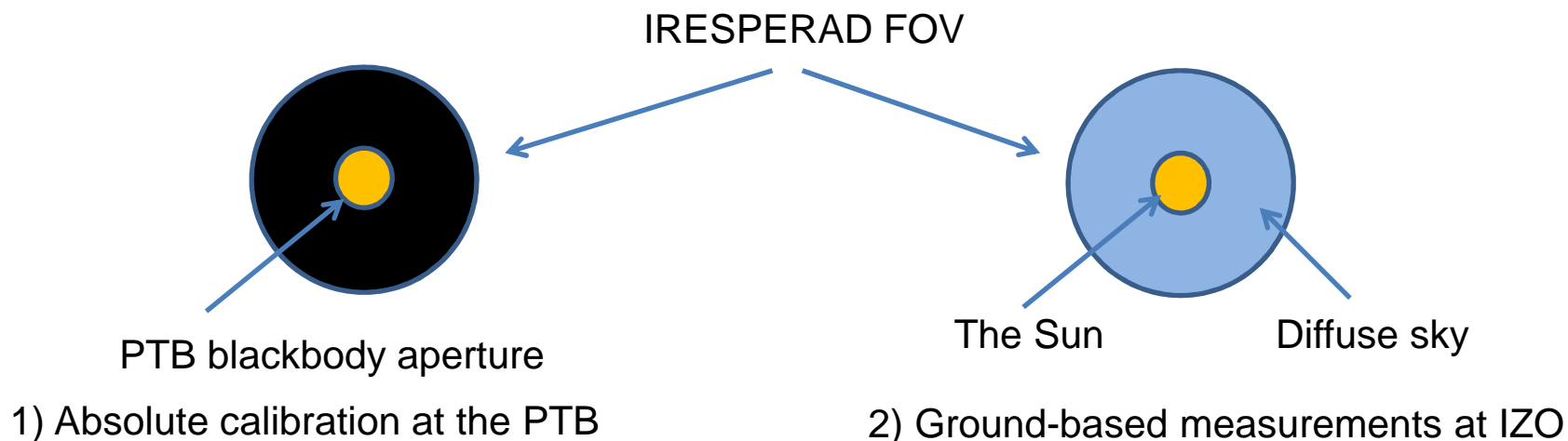


“At small absorber amounts there is a transition from a square root to a linear law.” [linear law for Transmission as a function of AMF -> Beer-Bouguer-Langley law is valid -> Langley plot method is valid] [Thome et al 1994].



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Contribution of Circumsolar radiation



The contribution of the circumsolar radiation has been investigated

Error in Determining I_0^λ due to Diffuse/Circumsolar radiation: $\delta(I_0^\lambda)$

$$\delta(I_0^\lambda) \propto \text{altitude}^{-1}, \lambda^{-1}, AOD [\text{Shaw, 1975}]$$

Calculations for a reference campaign day (2nd june) using LIDORT:

$$\delta_{\max}(I_0^{870}) \sim 0.16\%$$

$$\delta_{\max}(I_0^{1020}) \sim 0.10\%$$



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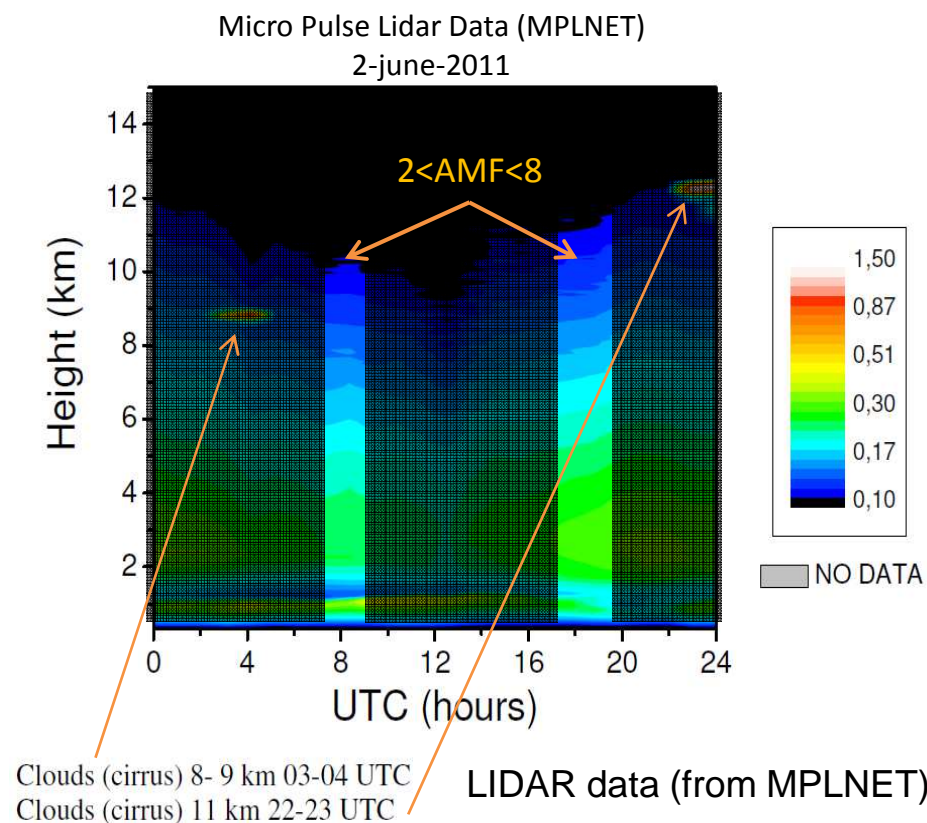
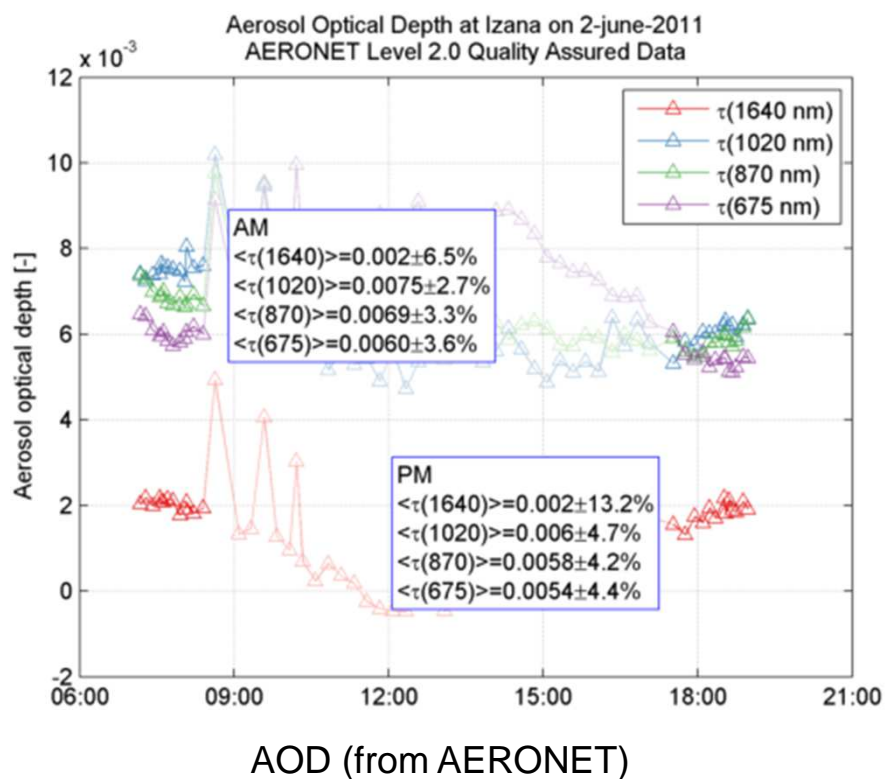
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The site

High-mountain Izaña Observatory (IZO)

Possible presence of cirrus clouds?

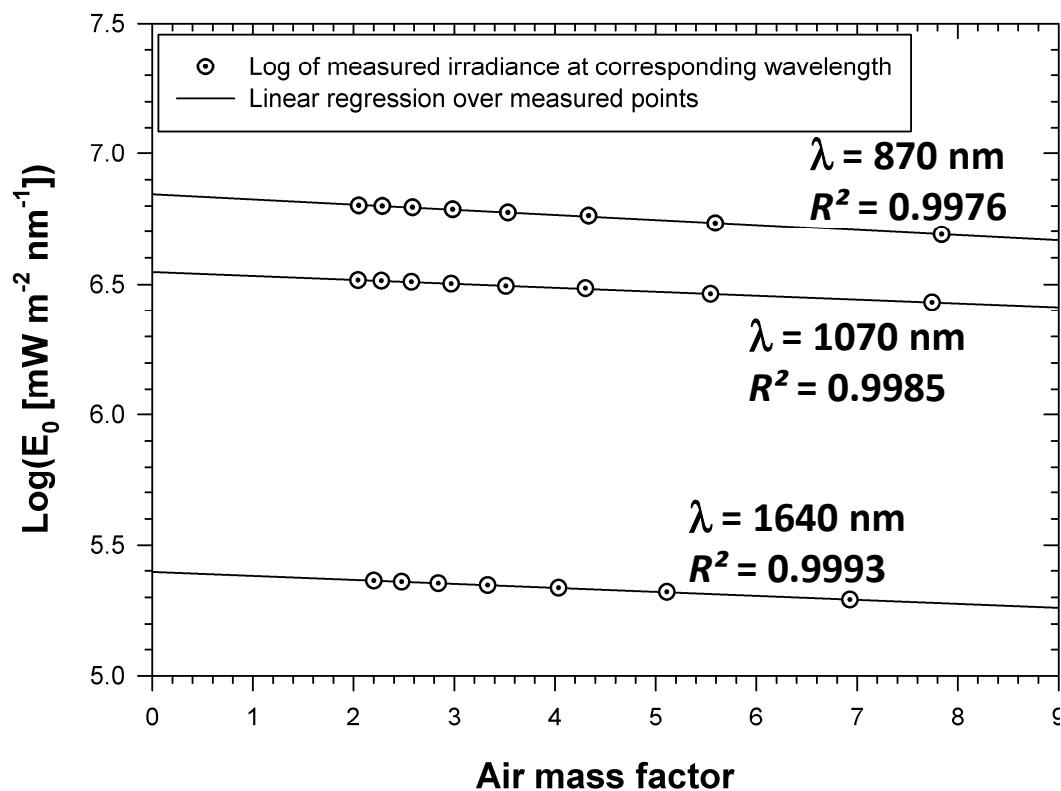
Exemple from a measurement reference (clear sky) day: 2^d June 2011



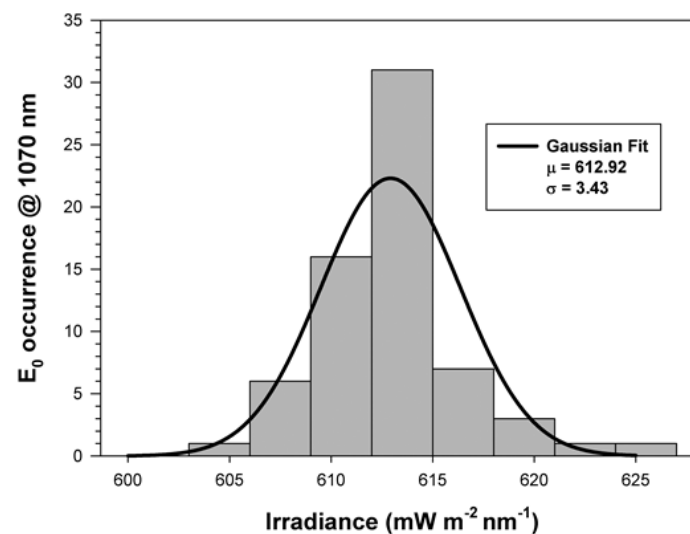


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NIR measurements (IRESPERAD)



From Bouguer-Langley methodology

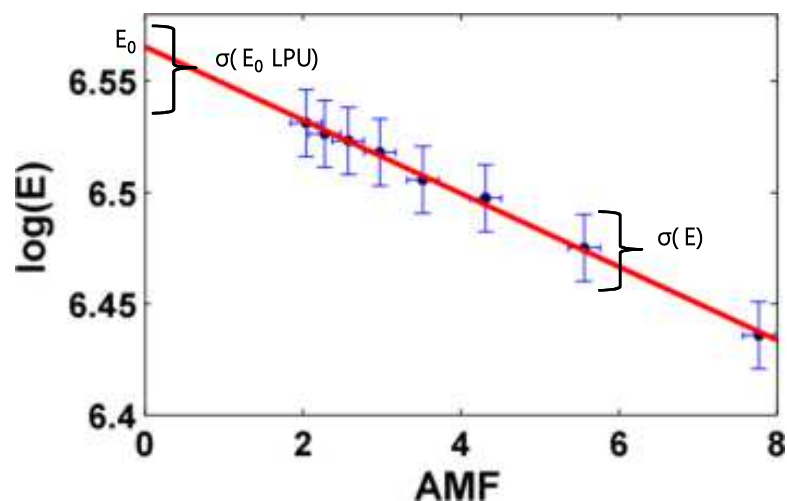


Gaussian fit for the 164 channels:
 → example for $\lambda = 1070 \text{ nm}$



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Results & uncertainties

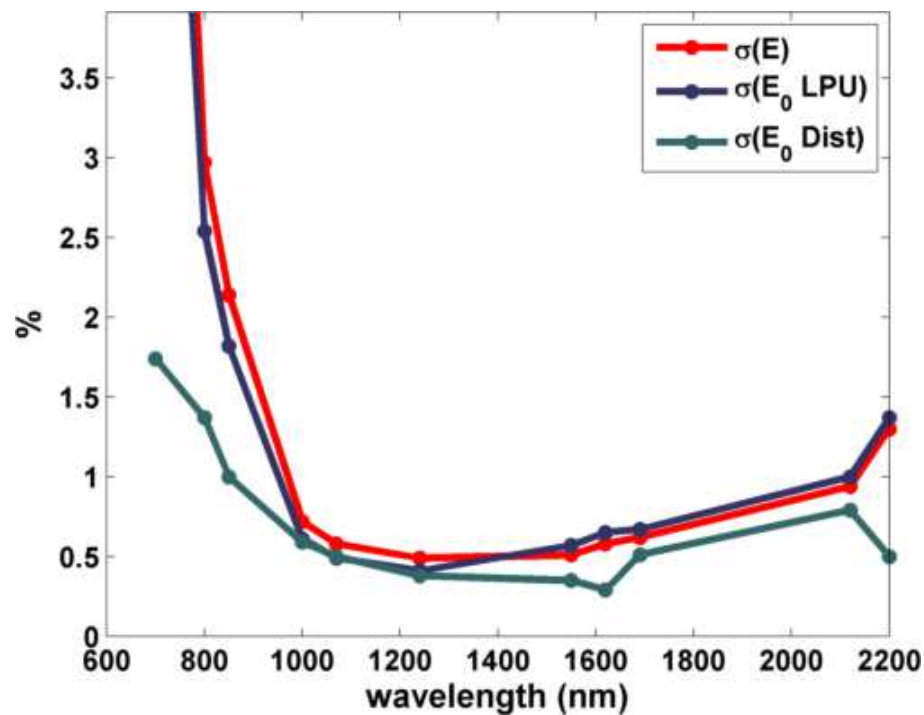


$\sigma(E_0)$? Starting from each $\sigma(E)$ calculated from the LPU

LPU merged into linear regression (Krystek M. and Anton M., 2007)

Dependent on $\sigma(E)$

$\sigma(AMF)$ negligible





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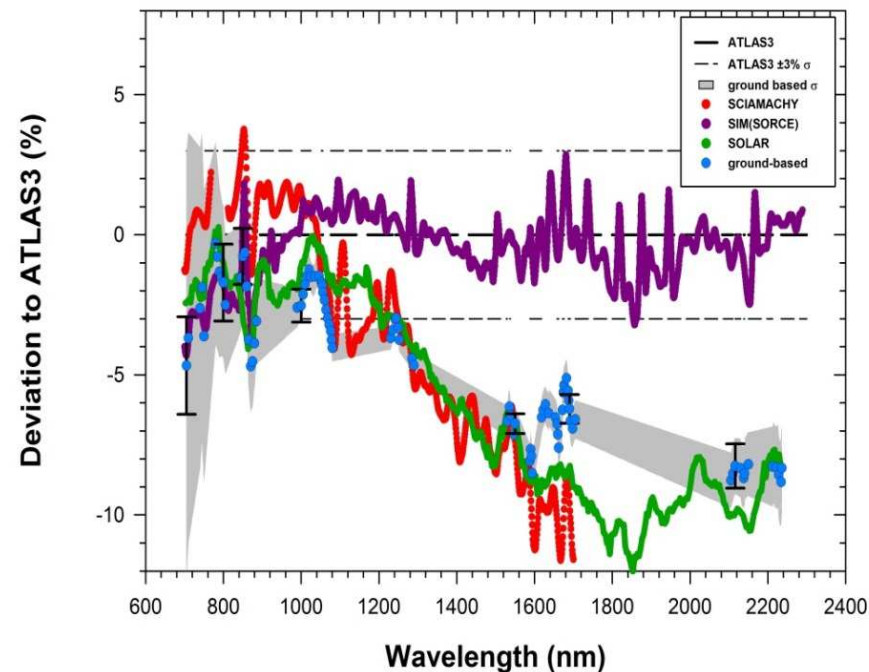


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NIR measurements (IRESPERAD)

Ground-based measurement campaign at Izaña Observatory (IZO), May-October 2011

→ *Discussions on the discrepancies observed between NIR measurements from space that motivated the realization of a ground-based measurement campaign*



Bolsée et al., Accurate Determination of the TOA Solar Spectral NIR Irradiance Using a Primary Standard Source and the Bouguer-Langley Technique, *Solar Physics*, 289, Issue 7, 2433-2457, 2014, doi; 10.1007/s11207-014-0474-1.



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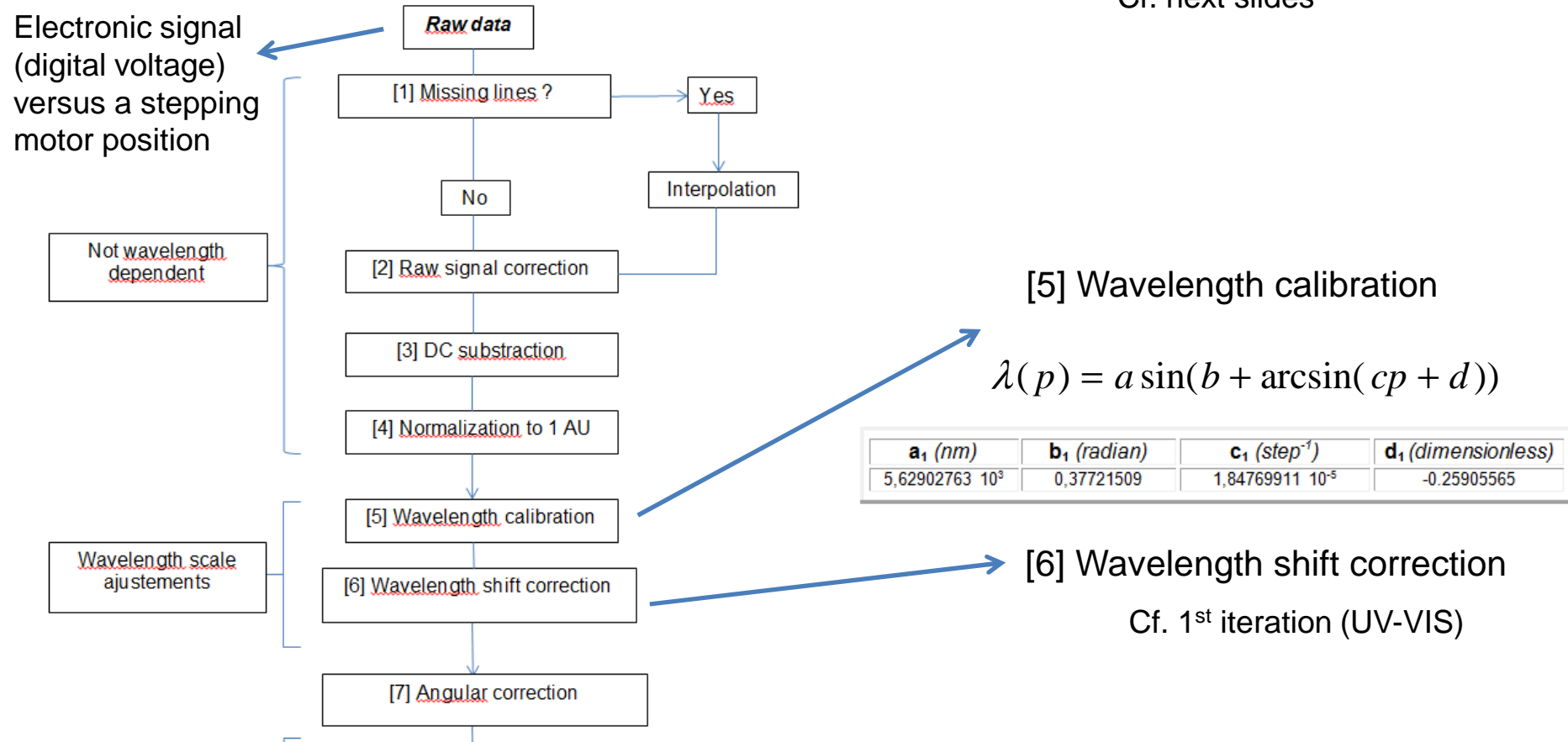


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SOLAR/SOLSPEC IR channel – Flow chart

[2] Raw signal correction

Cf. next slides

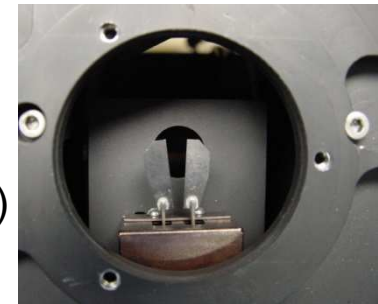




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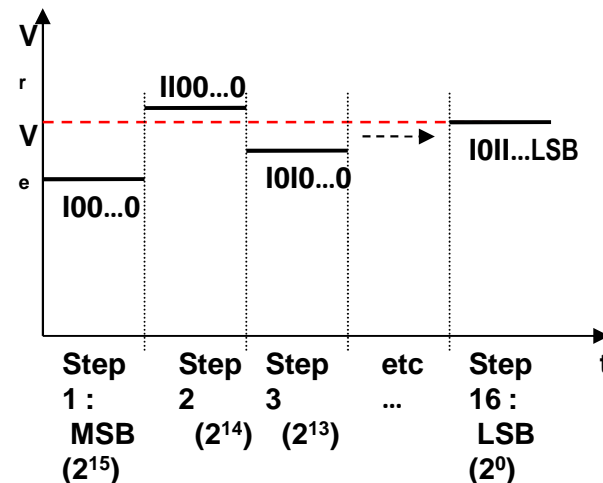
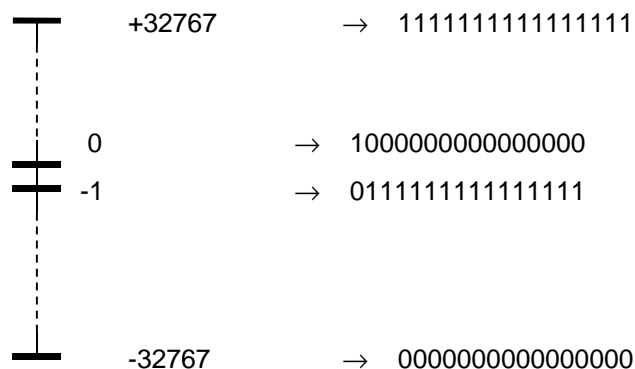
New IR electronics (BIRA-IASB)

- Chopper at 512 Hz
- PbS detector → signal converted in voltage, x 1000 (pre-Amplificator.)
→ Phase sensitive detection:
- Signal compared to the reference
- Amplification x 2.5, signal extracted and rectified
- Low-pass filter HR-4BLI-MG → signal VDC (with negative offset)



Final amplification → providing 3 gains (x1, x10, x40)

AD conversion using the 7805ALPRP (Maxwell Technologies Company) 16 bits converter
→ range (± 10 volts) converted to -32768 to 32768 'digital voltage'

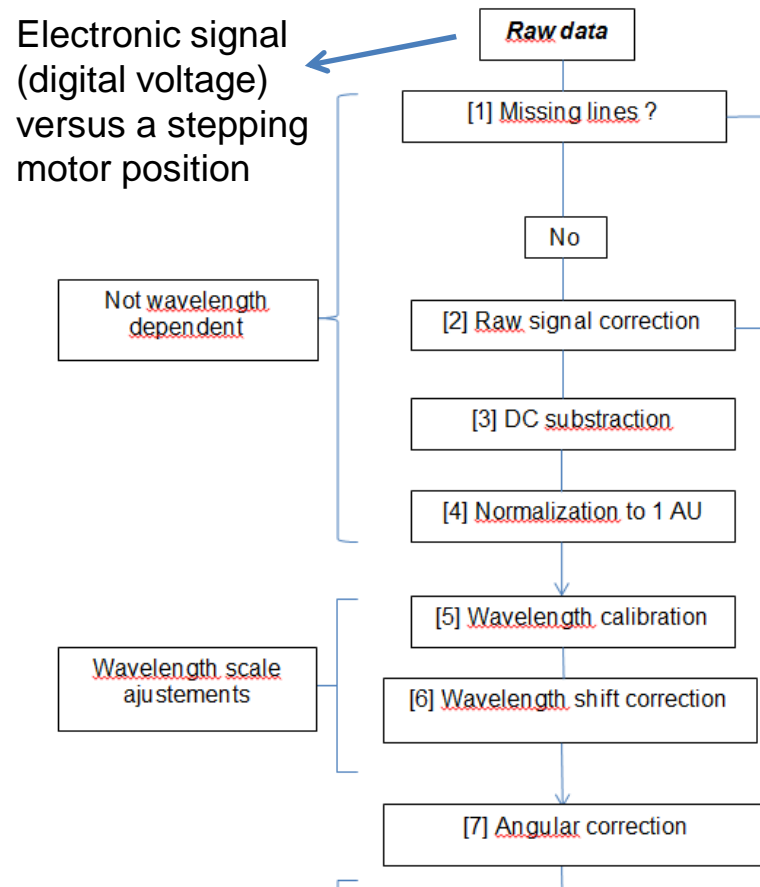


One reading of IR1, 2, 3
→ 102 μ s
One line of telemetry
<> of 2eN readings
N = 7, 10, ...



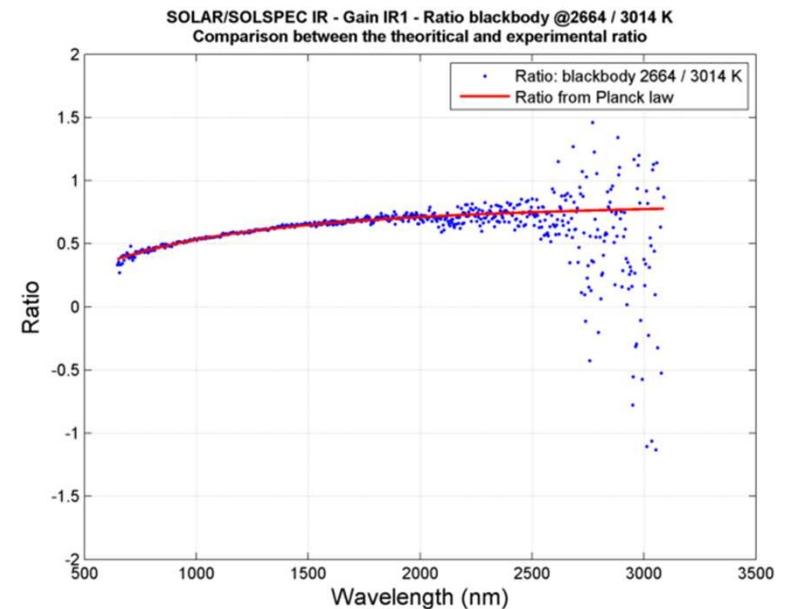
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IR channel – Flow chart



[2] Raw signal correction

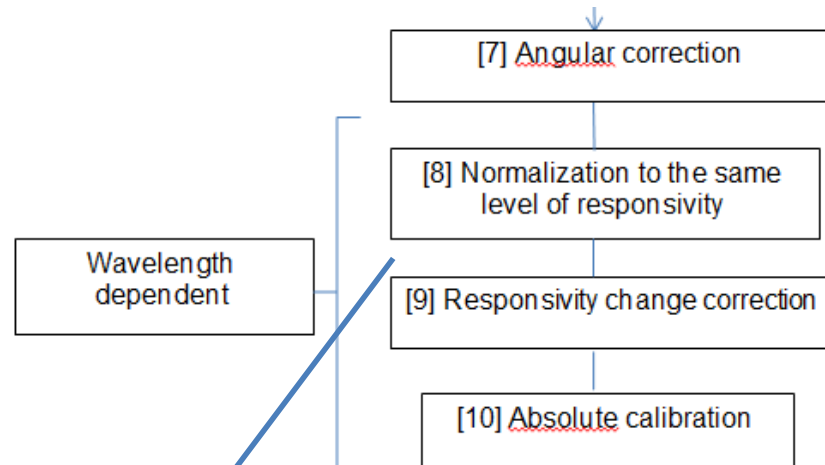
- IR2 taken as the reference
- Small adjustments of IR1 & IR3, confirmed by the good correspondence between the measured and theoretical ratio
'blackbody 2664 / 3014 K'





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IR channel – Flow chart

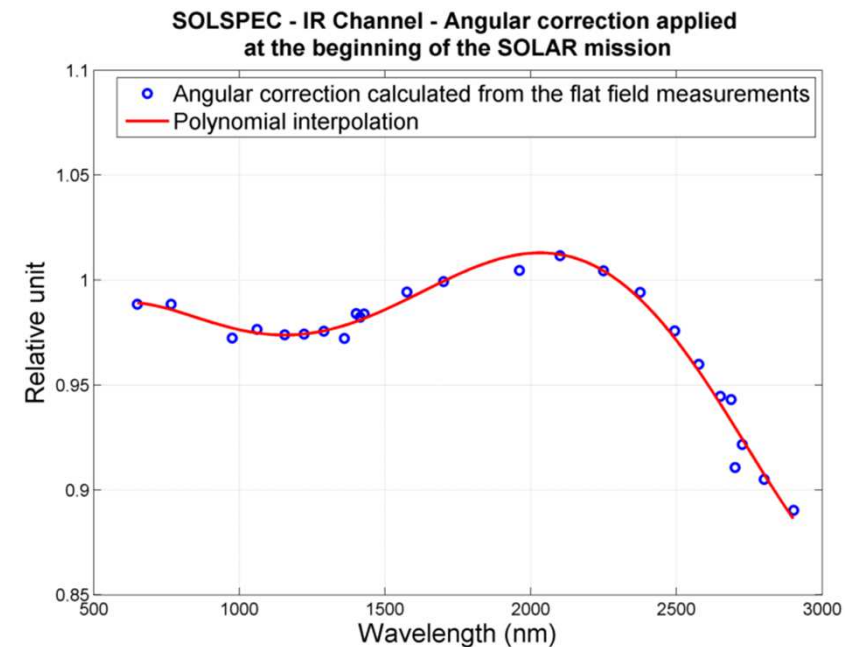


[8] Normalization to the same level of responsivity

- Seems to have 2 levels for the UV ('L', 'H')!
- Ongoing work for this study (classification, normalization).

[7] Angular correction

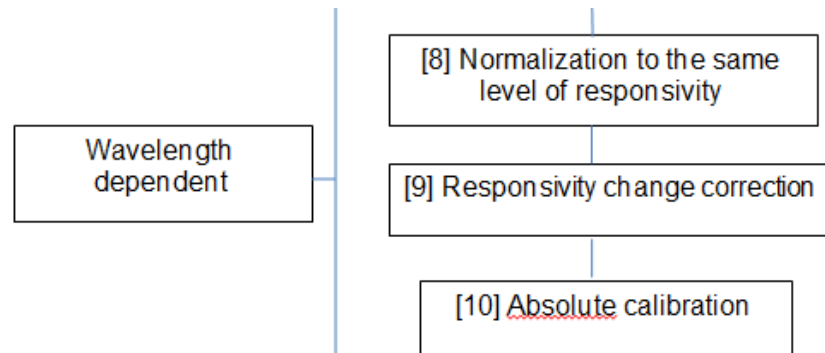
If required (for example, at the beginning of the SOLAR mission)





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IR channel – Flow chart



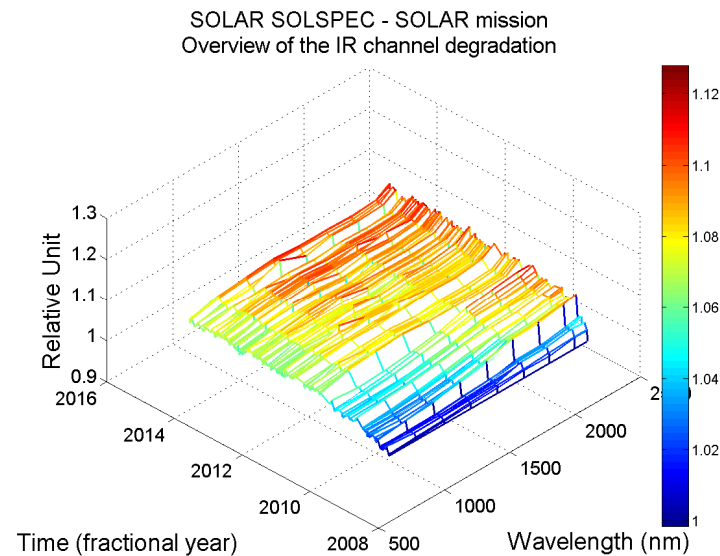
[9] Responsivity change

1) During the mission

IR channel responsivity

→ increase (~10 %) during the SOLAR mission

→ Monitoring of the aging, using the internal tungsten lamps or the Sun



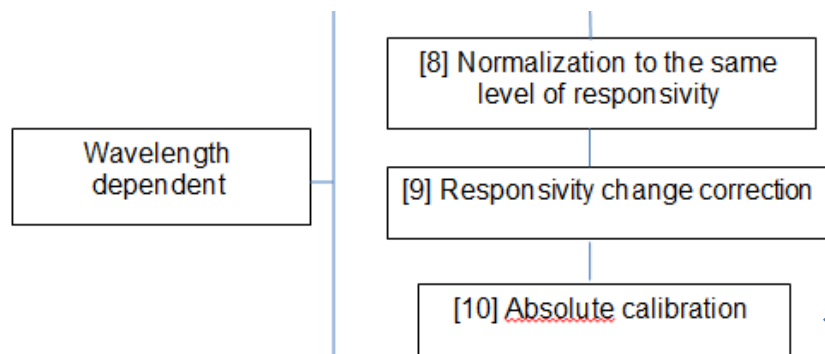
Using the SSI as relative standard



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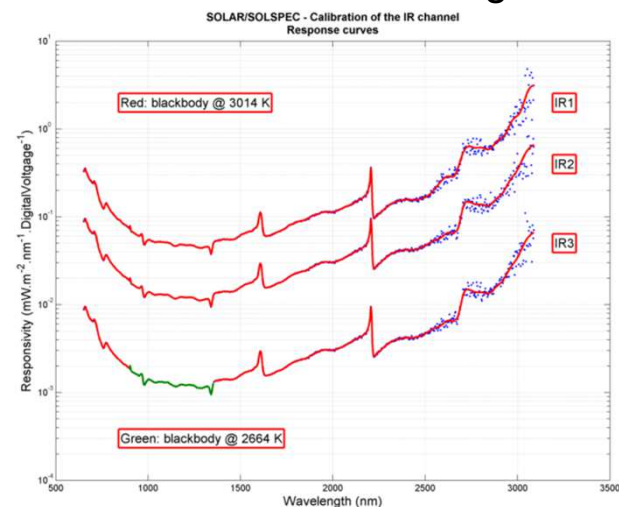
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IR channel – Flow chart

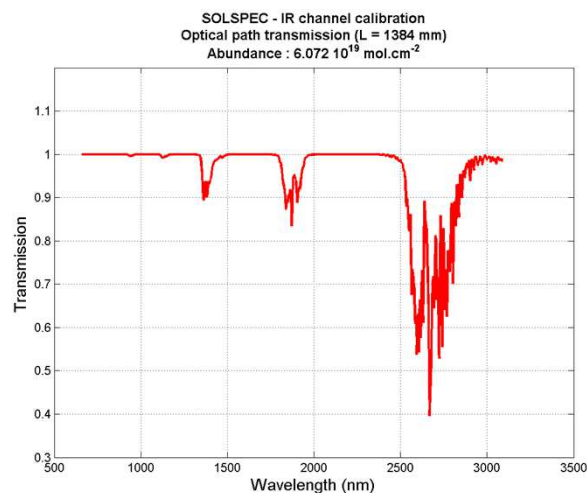


[10] IR channel → Absolute calibration

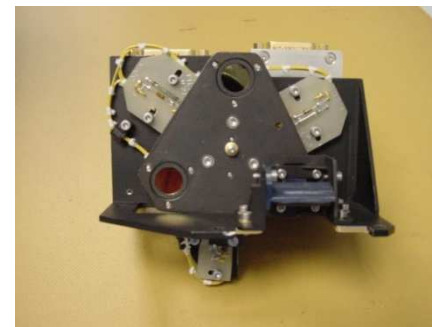
Blackbody (PTB) → 642 nm to 3088 nm
+ use of NIST 1000 W tungsten lamps



IR channel → Importance of the correction of the water vapor absorption for an accurate absolute calibration



IR filter wheel for second order rejection

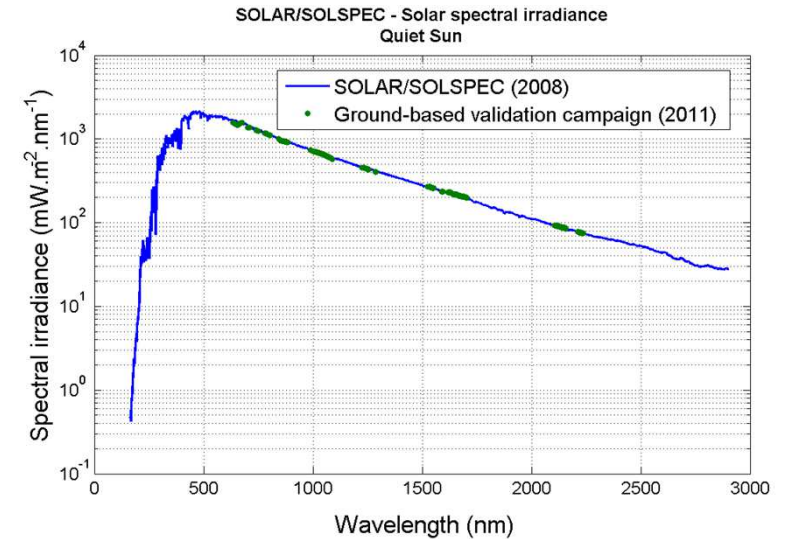
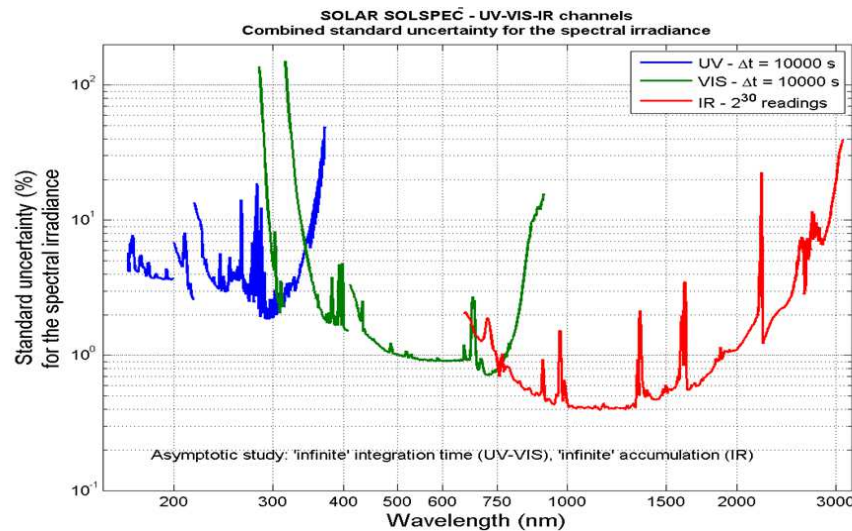


PTB: transmittance of the optical path (1.384 m)
between the BB and SOLSPEC



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SOLSPEC spectrum obtained



TSI estimation: $(1357,1 \pm \sim 15)$ W/m²

→ *Result: uncertainties (1σ)
for the solar measurements*



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Discussion on:

'The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station', G. Thuillier et al., 2015

Linked to:

'Comments on the Article by Thuillier et al., 'The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station', M. Weber, invited review, 2015

→ *The main part of this review is to document the Sciamachy NIR spectrum*

Some other comments will be discussed :

- 1) The uncertainty estimation of the ATLAS 3 spectrum*
- 2) The sensitivity of the SOLSPEC electronic to thermal effects*
- 3) The stability of the SOLAR/SOLSPEC electronics*
- 4) The uncertainty of IRESPERAD measurement*



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1) *The uncertainty estimation of the ATLAS 3 spectrum*

→ *Estimated to be equal to 3 % in the IR*

Thuillier, G. et al., The Solar Spectral Irradiance from 200 to 2400 nm as Measured by the SOLSPEC Spectrometer from the ATLAS and EURECA Missions, Solar Physics, 214, 1-22, 2003

But it is stated in this paper:

'(g) From the air transmission:

During the blackbody calibration, the instrument is flushed with dry nitrogen. However, the optical path length of 85 cm between the blackbody and the entrance diffuser is in air. But, this distance is too short to give a noticeable absorption in the IR range except around 1.35 μm and 1.9 μm where it could reach 0.1% due to H_2O absorption bands.'

→ In fact: the water vapor absorption is important even with 85 cm of optical path. This effect was NOT taken into account for ATLAS 3 and it could affect the absolute calibration.



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Correction of the water vapor absorption during the absolute calibration of an instrument such as SOLSPEC

Detection for SIM & SOLAR/SOLSPEC

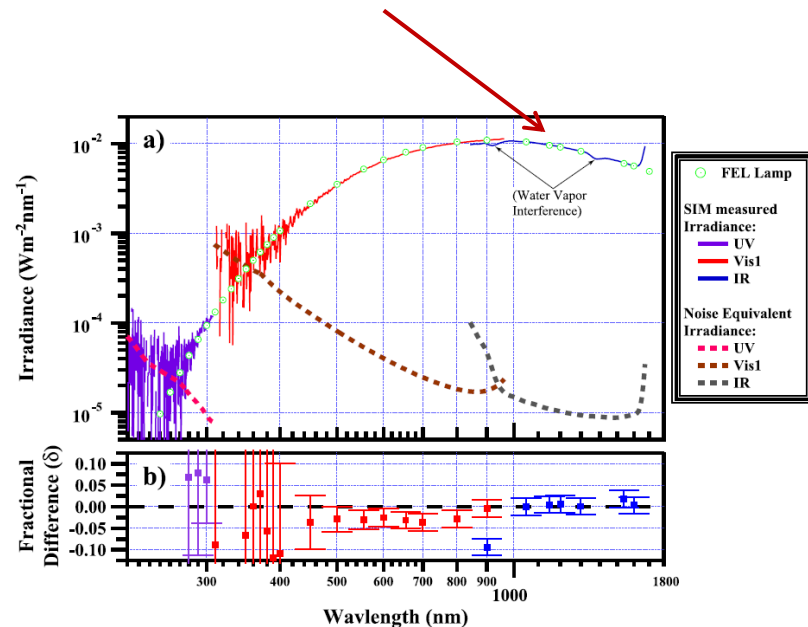
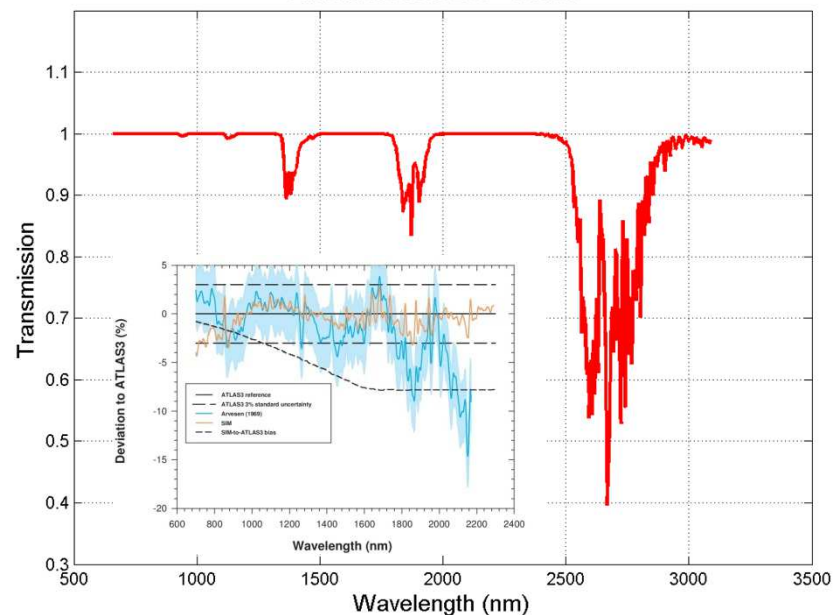


Figure 2 Comparison of SIM to a NIST certified FEL lamp as measured by the three SIM focal plane photodiodes. The lamp was located 2.24 m in front of the entrance slit to produce an approximate 0.5° divergent light beam to illuminate the instrument in the same manner as the Sun; the lamp intensity is $\approx 2.5\%$ of the solar intensity. The graph also shows the curves of noise equivalent irradiance to indicate where the measurements are dominated by noise. The bottom panel shows the fractional difference (SIM-FEL)/FEL over the full range of the experiment.

SOLSPEC - IR channel calibration Optical path transmission ($L = 1384 \text{ mm}$) Abundance : $6.072 \cdot 10^{19} \text{ mol.cm}^{-2}$



Harder, J. W., Thuillier, G., Richard, E. C., Brown, S. W., Lykke, K. R., Snow, M. McClintock, W. E., Fontenla, J. M., Woods, T. N. and Pilewskie, P., *The SORCE SIM Solar Spectrum: Comparison with Recent Observations*, *Solar Physics*, 263, 3-24, 2010, doi: 10.1007/s11207-010-9555-y.



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The uncertainty estimation of the ATLAS 3 spectrum

→ *So, the estimation of 3 % of standard uncertainty for the ATLAS 3 IR spectrum (constant for all wavelengths) must be revised at least at some spectral bands because the water vapor absorption was not taken into account.*

Also, the problems with the design of SOLSPEC/ATLAS design of the IR electronic discovered at the time of the refurbishment (after the ATLAS 3 publication) should be taken into account. Ideally, the ATLAS 3 (SOSP) raw data should be reprocessed.



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2) The sensitivity of the SOLSPEC electronic to thermal effects

In 'The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station', G. Thuillier *et al.*, 2015,

it is stated that:

2.3. Spectra from ATLAS 1 and 3 and SOLAR 1 and 2

Using data from the three ATLAS missions and the EURECA mission, two spectra were built (Thuillier *et al.*, 2004):

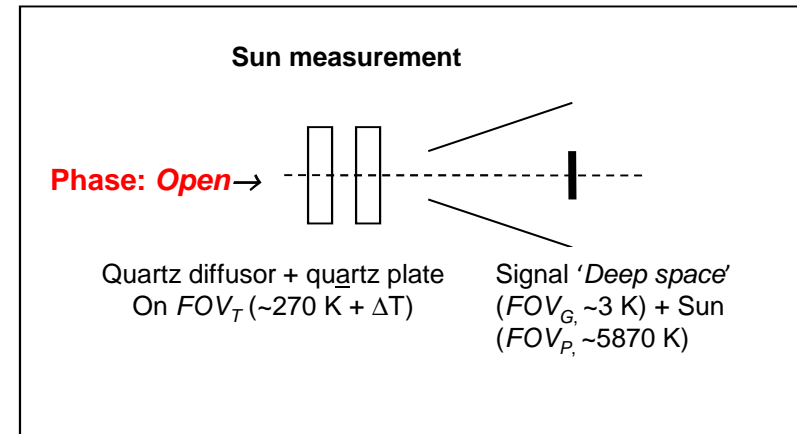
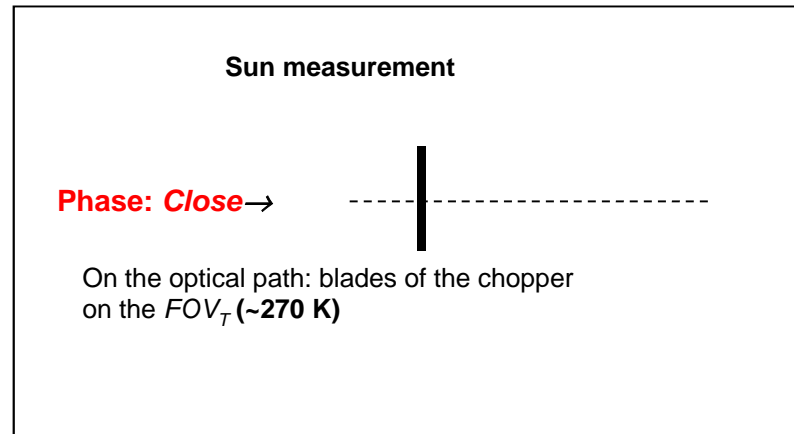
- ATLAS 1 at high solar activity, and ATLAS 3 at low solar activity. For both spectra the IR range was provided by the SOSP/EURECA because the temperature of the platform was low and stable enough to allow IR measurements. The ATLAS 1 and 3 spectra are a

→ In fact, the phase sensitive detection of SOLSPEC is designed in such a way to be insensitive to the temperature of the instrument, because:

- 1) The PbS detector is at a constant T° of -20°C ,
- 2) The thermal emission of SOLSPEC out of the optical path is not chopped (→ not detected)
- 3) For the thermal emission of the optical path, (diffusor, chopper blades, ...) we have:



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- For the spectral range of the IR channel of SOLAR/SOLSPEC (0,7 to 3 μm), the thermal emission is always 10^{-6} lower than the SSI. The situation was similar for SOLSPEC 1st generation (except that the chopper was in front of the exit slit).
- In conclusion, the lack of IR results from the SOLSPEC ATLAS & SpaceLab missions (Space Shuttle), in comparison with the SOSP (EURECA platform) mission, can not be attributed to the thermal environment. The electronic malfunction of the 1st generation of the instrument should be considered.



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3) The stability of the SOLAR/SOLSPEC electronics

In 'The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station', G. Thuillier et al., 2015,

it is stated as a main conclusion that:

(Thuillier *et al.*, 2014). We presented a methodology that corrects for this factor and demonstrates that the previously noted deviation between ATLAS 3 and the published SOLAR 2 is reconciled by the new treatment of the instrument response at first light when the IR spectrometer had not reached its permanent regime.

An important consequence of this study is that the calibration coefficients determined at PTB are correct if applied when the instrument comes to stabilization.

- This is in contradiction with the experimental data collected from two independent tungsten lamps of SOLAR/SOLSPEC, 1) at the time of the PTB absolute calibration and 2) at the beginning of the SOLAR mission in 2008.
- In consequence, the PTB calibration must be applied on the 2008 level of sensitivity and not the 2010 level. The following CASE 1 must be the only one acceptable.



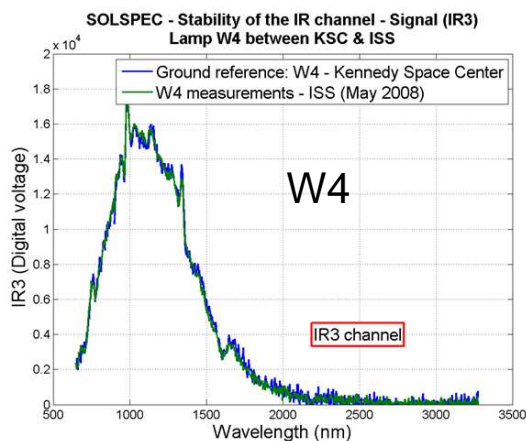
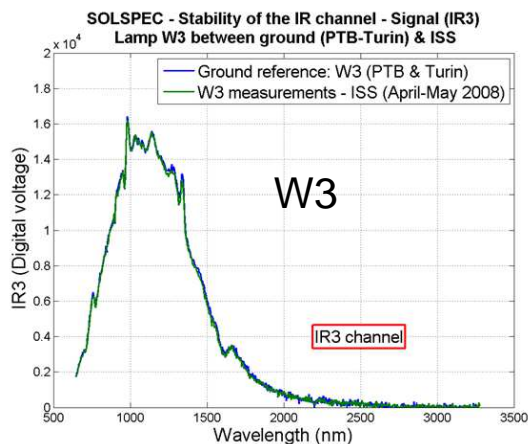
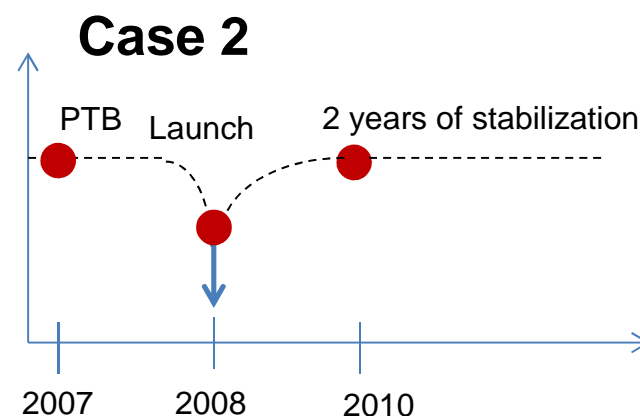
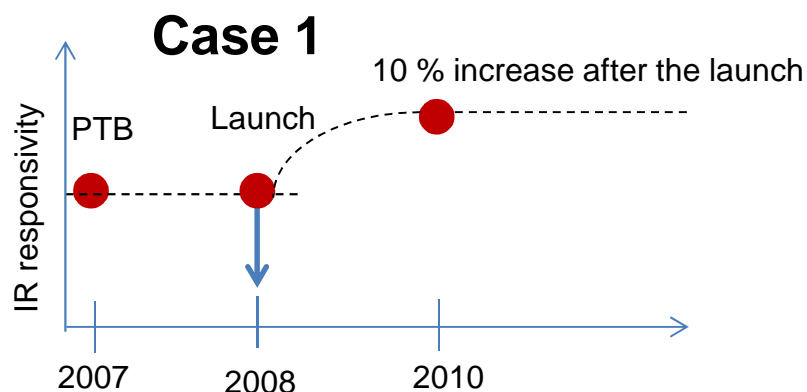
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SOLAR/SOLSPEC → IR measurements

SOLAR mission

IR channel responsivity → absolute level to be considered



Criteria provided by the internal lamps
→ **Case 1 must be validated**



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4) The uncertainty of IRESPERAD measurement

In 'The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station', G. Thuillier et al., 2015,

it is stated as another main conclusion that IRESPERAD measurements are not reliable as ground based measurements in the NIR and that the uncertainty estimations are underestimated:

We presented evidence that the claimed uncertainties of the IRESPERAD are too small. A difference of 7 % (at 1 700 nm) of the ground-based observations to ATLAS 3 can be explained by a combination of several sources of the uncertainty, including the inevitable small remaining absorption and error generated by the variation in time of the total absorbing species concentration. We emphasize that the IRESPERAD spectrum is not the spectrum that has been measured on ground, but has been extrapolated to remove the absorption of the terrestrial atmosphere. The bases of the extrapolation (hypothesis of the Bouguer–Langley method) are stable atmosphere properties over a day, which is unlikely to ever be the case.

→ As a remind:

“... mountain tops like Mauna Loa in Hawaii or Izaña in Tenerife provide environments where the constancy of the optical depth is frequently assured...these results [Langley plots] are rarely controversial.” [Kiedron & Michalsky, 2015]

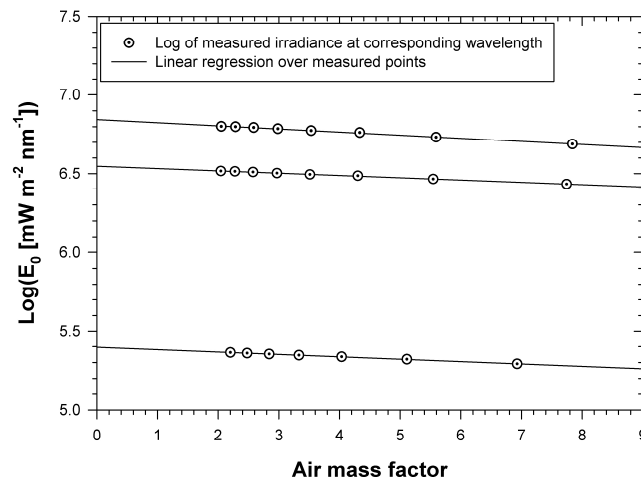
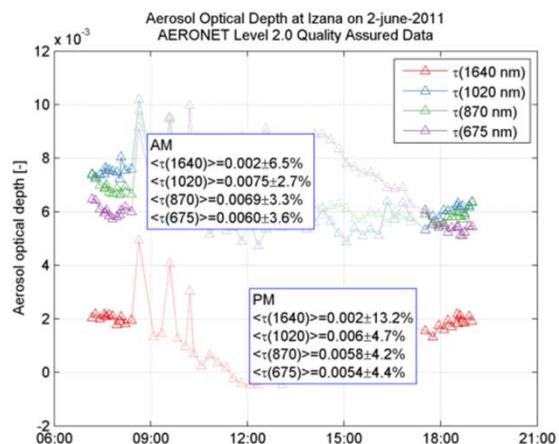


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From the IREPERAD data processing:

- Reliable Langley plots with correlations as high as 0.99 to 0.999 demonstrated the stability of the atmospheric conditions during many half days at IZO.
- A sample of 66 half days with optimal weather conditions was collected during the campaign, providing estimation of TOA SSI with a dispersion as low as 0.5 %.
- We demonstrated by LPU calculations, the high accuracy of our measurements using the blackbody of the PTB as primary standard, and reliable relative standards (NIST FEL lamps) for maintaining the calibration during the whole campaign.

IRESPERAD measurements were demonstrated to be reliable. The only few objective adjustments that could be discussed will never explain the 8 % of discrepancies with respect to ATLAS 3.





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Conclusions:

- The estimation of the standard uncertainty of ATLAS 3 is to be revised for some spectral range related to the water vapor absorption.
- From experimental data, the absolute response of SOLAR/SOLSPEC was the same in 2008 than at the PTB,
- IRESPERAD provided accurate measurements of TOA SSI in the NIR.
- New NIR measurements are required.



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Thank you for your attention!