FRC-5

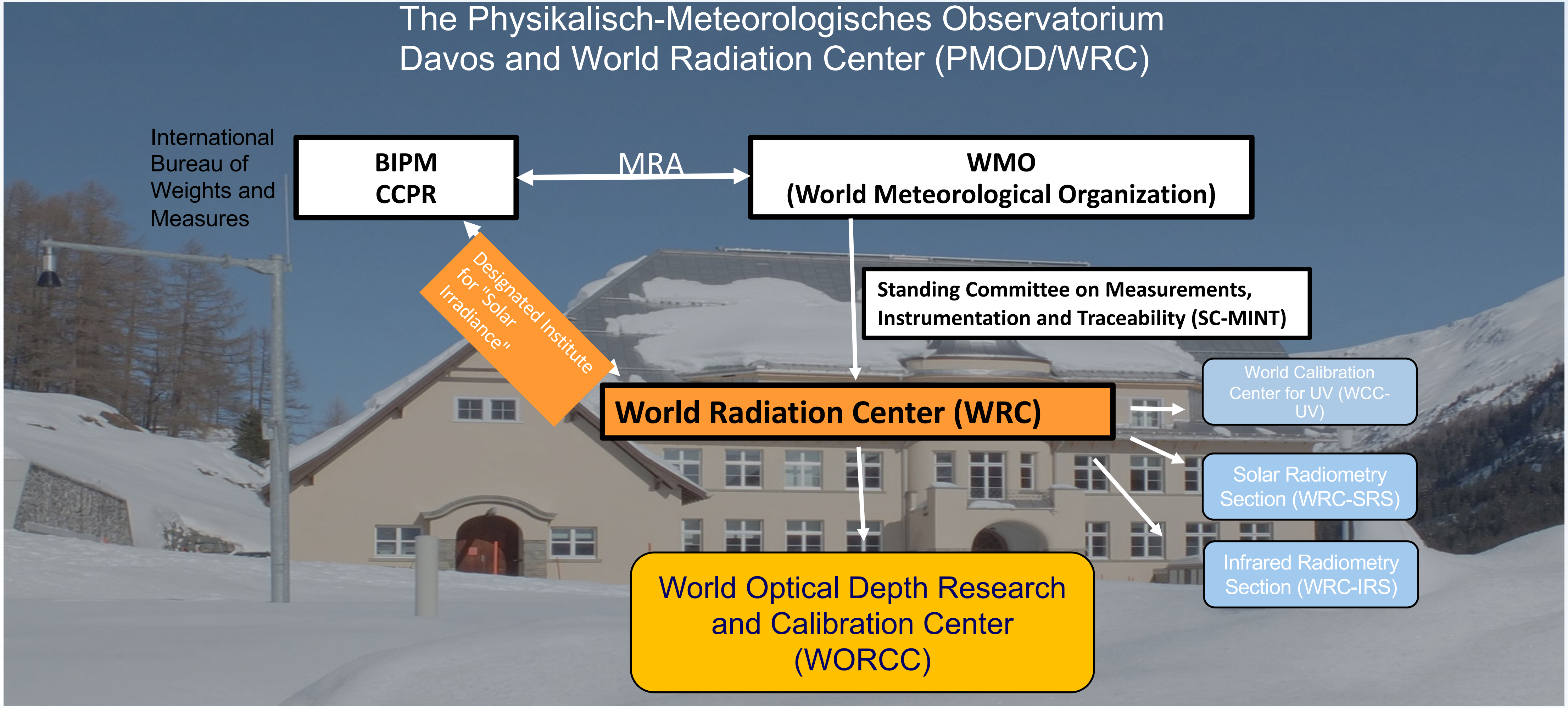
The Global Atmospheric Watch and homogenization activities of aerosol networks at PMOD/WRC

PMOD/WRC
Physics Meteorology Observatory Davos,
World Radiation Center, Switzerland

Stelios Kazadzis, N. Kouremeti and J. Gröbner

Davos, FRC-5, 29.09.2021

PMODWRC aerosol remote sensing



Aerosol Optical Depth *(AOD) is a quantitative estimate of the amount of aerosol present in the atmosphere it is a measure of the extinction of a ray of light as it passes through the atmosphere. (main aerosol radiative impacts variable)*

The Global Atmospheric Watch of WMO

Addressing atmospheric composition on all scales: from global and regional to local and urban.

The mission of GAW is to:

• Maintaining and applying global, long-term observations composition and selected physical characteristics of the atmosphere emphasizing quality assurance and quality control

• Reduce environmental risks to society and meet the requirements of environmental conventions

to support:

- *the United Nations Framework Convention on Climate Change (UNFCCC),*
- *the Global Climate Observing System (GCOS),*
- *the Intergovernmental Panel on Climate Change (IPCC) and to*
- *the development of Global Framework for Climate Services (GFCS)."*

WORLD METEOROLOGICAL ORGANIZATION
Weather · Climate · Water

GAW Station Information System (GAWSIS, http://gawsis.meteoswiss.ch)

The Global Atmospheric Watch of WMO

WORLD METEOROLOGICAL ORGANIZATION
Weather · Climate · Water

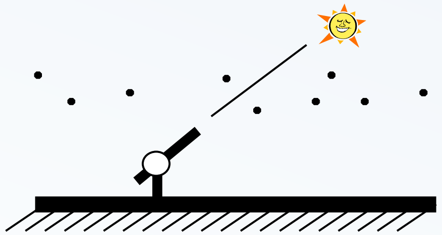
Addressing atmospheric composition on all scales: from global and regional to local and urban.

ECV: multi-wavelength Aerosol Optical Depth

WMO has designated PMODWRC - World Optical depth Research and Calibration Center (WORCC) as the primary aerosol optical depth (AOD) reference center.

WORCC provides the traceability of AOD measurements guaranteeing the data quality needed in climate studies

Essential Climate Variables: Aerosol Optical Depth (AOD)



Signal
Volts (λ)

→

Calibration
Post processing (Atm. inputs)
Clouds

→

AOD (λ)

unitless

$$I_\lambda = I_\lambda^0 * e^{-\tau_\lambda m}$$

$$T(\lambda) = \frac{\ln \frac{I_0}{I}}{m} - \sum_i \tau_{att(i)} m_{att(i)} / m$$

$$\tau_\lambda = \tau_{O3} + \tau_{aer} + \tau_{Ray} + \tau_{clouds} + \tau_{NO_2}$$

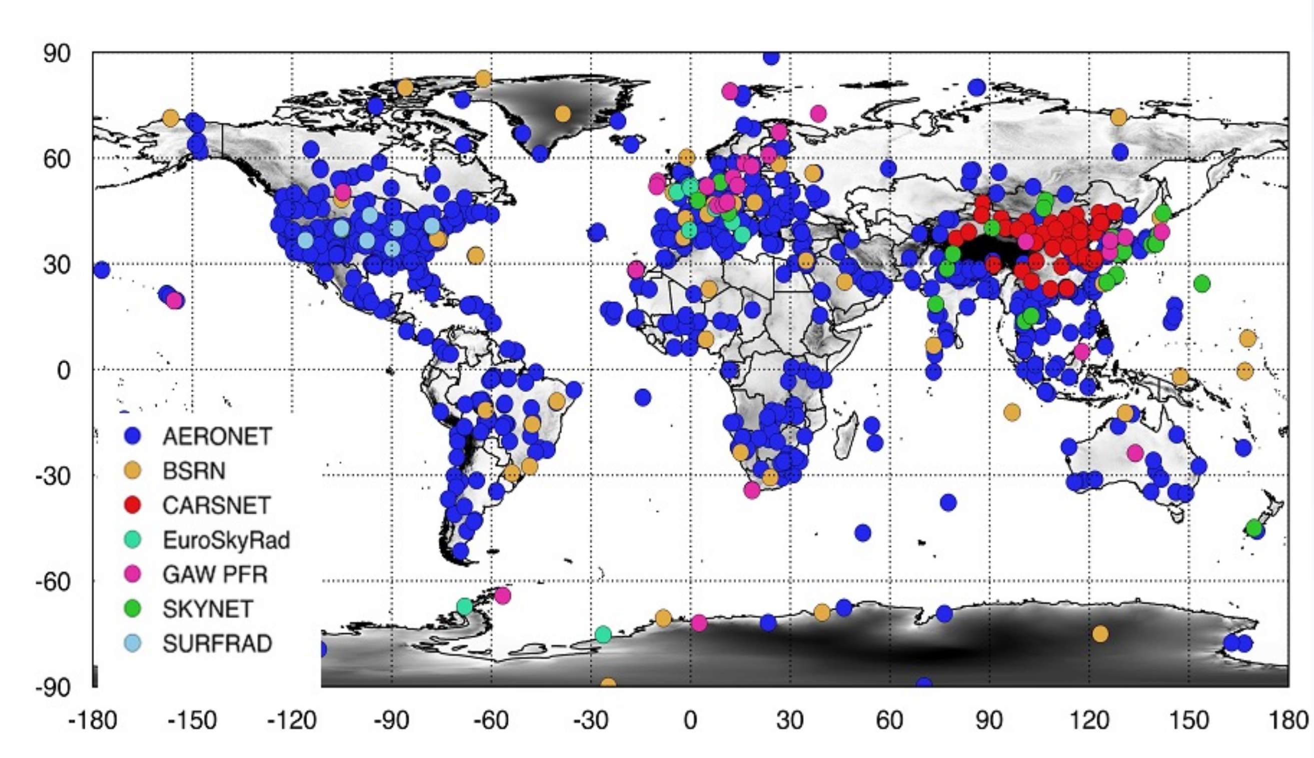
Instrument homogenization

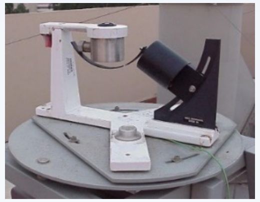
- Calibration
- Processing (inputs, algorithms)
- Instrument technical differences
- Maintenance & individual post corrections

WMO report 2016

AOD Networks

Global networks for aerosol remote sensing

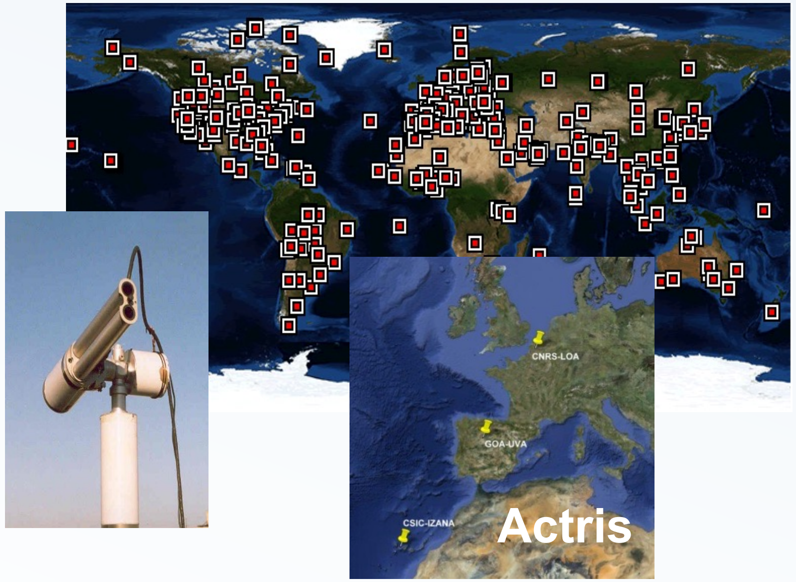




WORCC mandate: initiate global homogenization activities for sun-photometric AOD

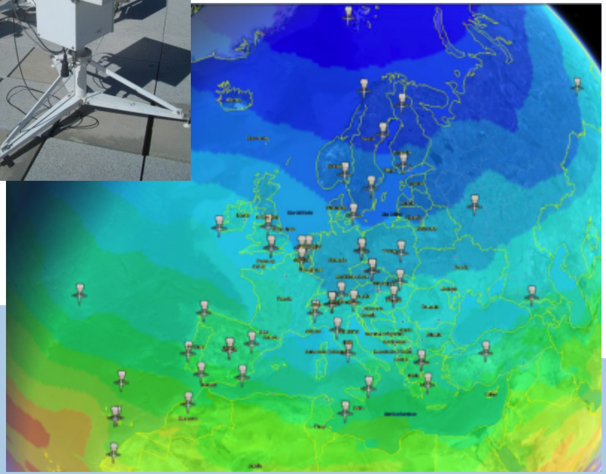
AOD Networks and calibration and post processing hierarchy

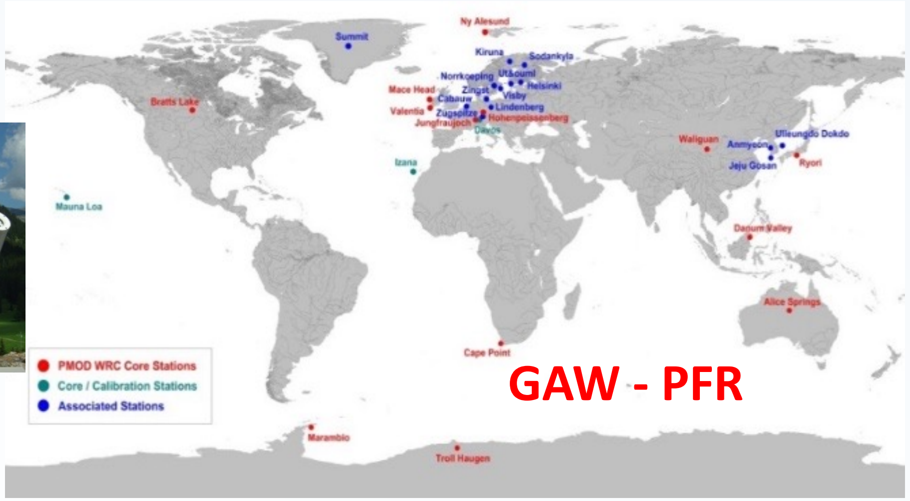
AERONET Europe



Skynet

Brewer EUBRWNET





Homogenization / reference Triad

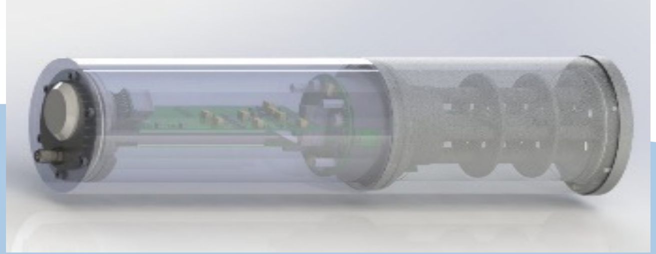
$$I_\lambda = I_\lambda^0 * e^{-\tau_\lambda m}$$

$$\tau_\lambda = \tau_{O3} + \tau_{aer} + \tau_{Ray} + \tau_{clouds} + \tau_{NO2}$$

- Definition of a reference scale or set of instruments

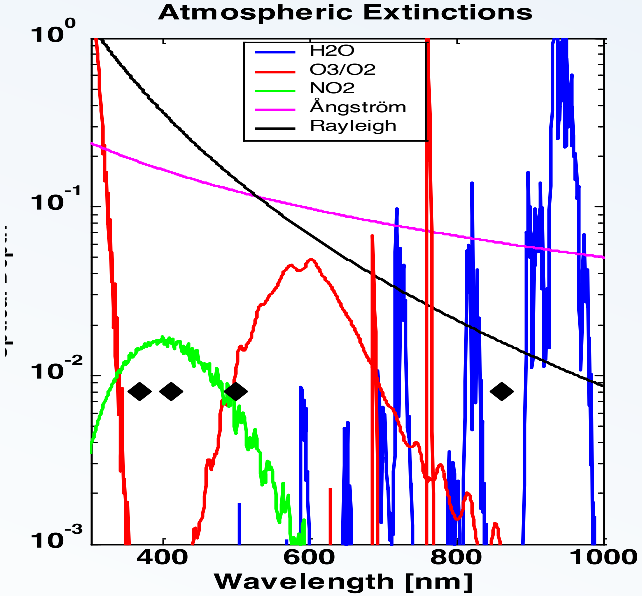
WMO has defined the World Optical depth Research and Calibration Center (WPRCC at PMODWRC) as the responsible institute/group for maintaining the AOD scale.

PFR Triad



WORCC/WMO reference

AOD @ 368nm, 412nm, 500nm, 865nm



Kazadzis et al., 2018

Homogenization Reference PFR triad

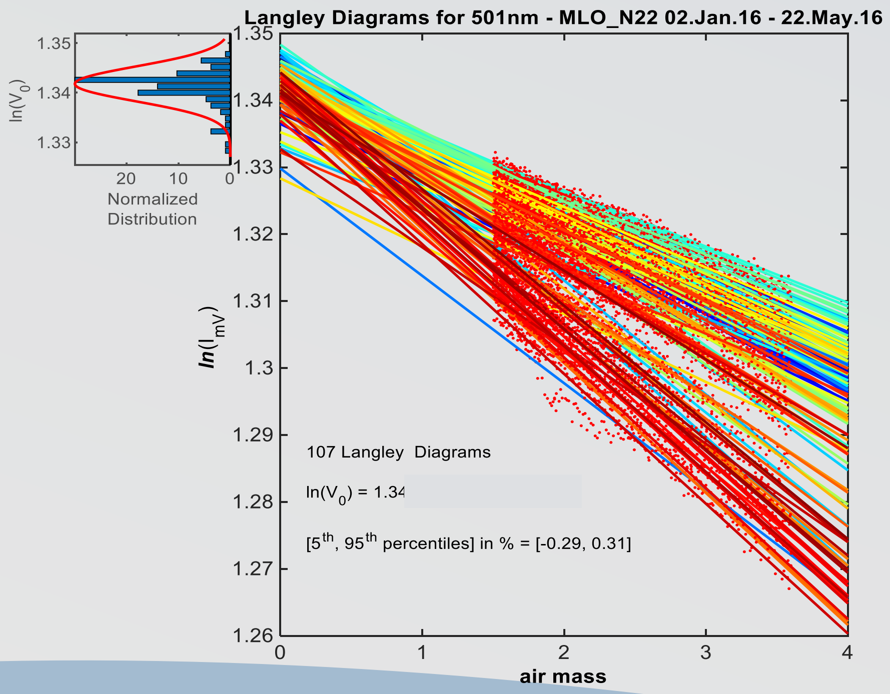
Langley calibration at high mountain stations
Relative calibration

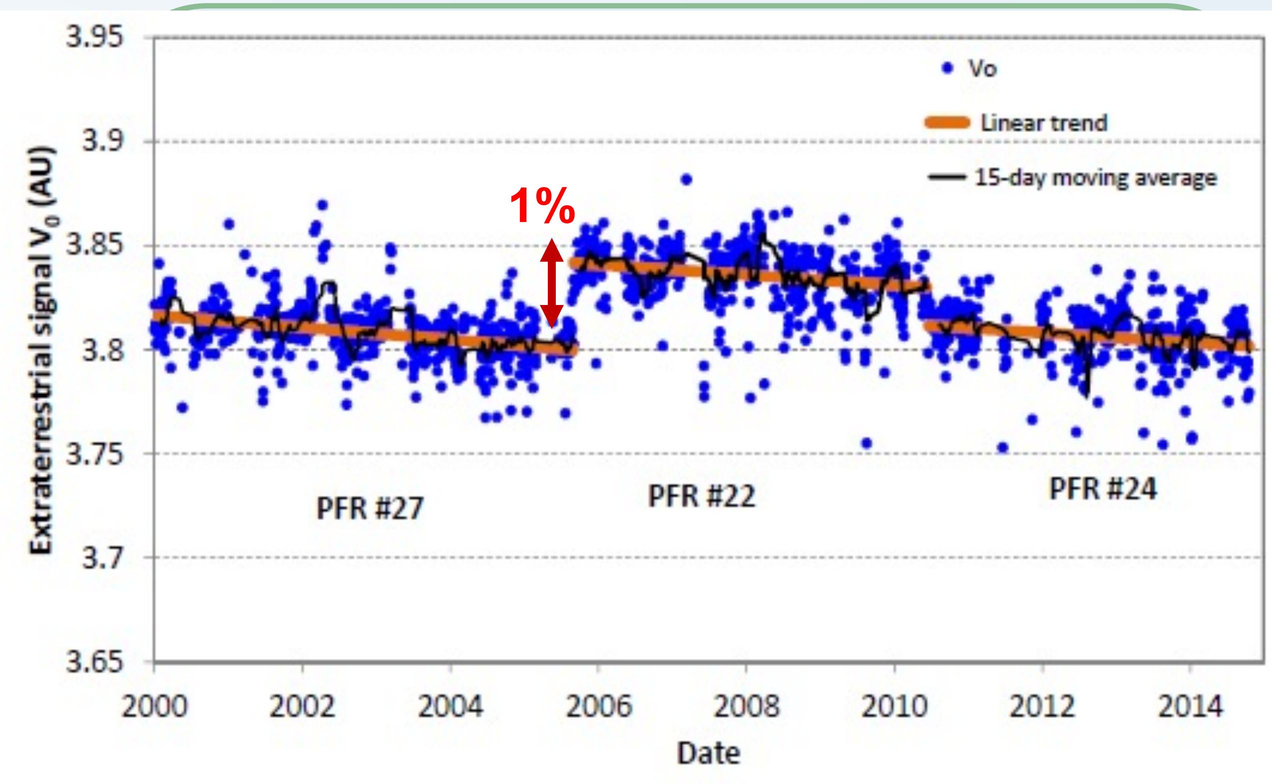
Top of the Atmosphere

$$I_\lambda = I_\lambda^0 * e^{-\tau_\lambda m} \qquad m = 0$$

Mauna Loa, PFR 2000-2015

Langley : Io= Vo , I=Signal (V)





Toledano et al., 2018

Long term stability of the reference PFR triad

- Definition of a reference scale or set of instruments

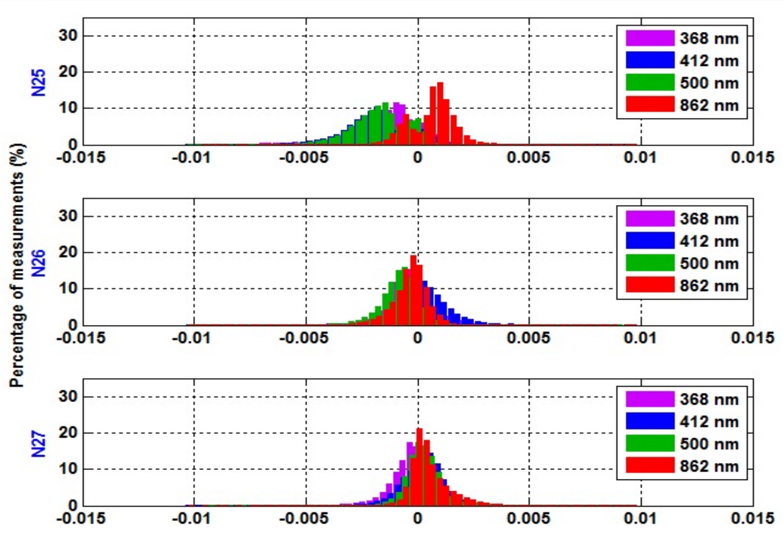
(U95): **95% within ±(0.005 + 0.01/m) op. depths**

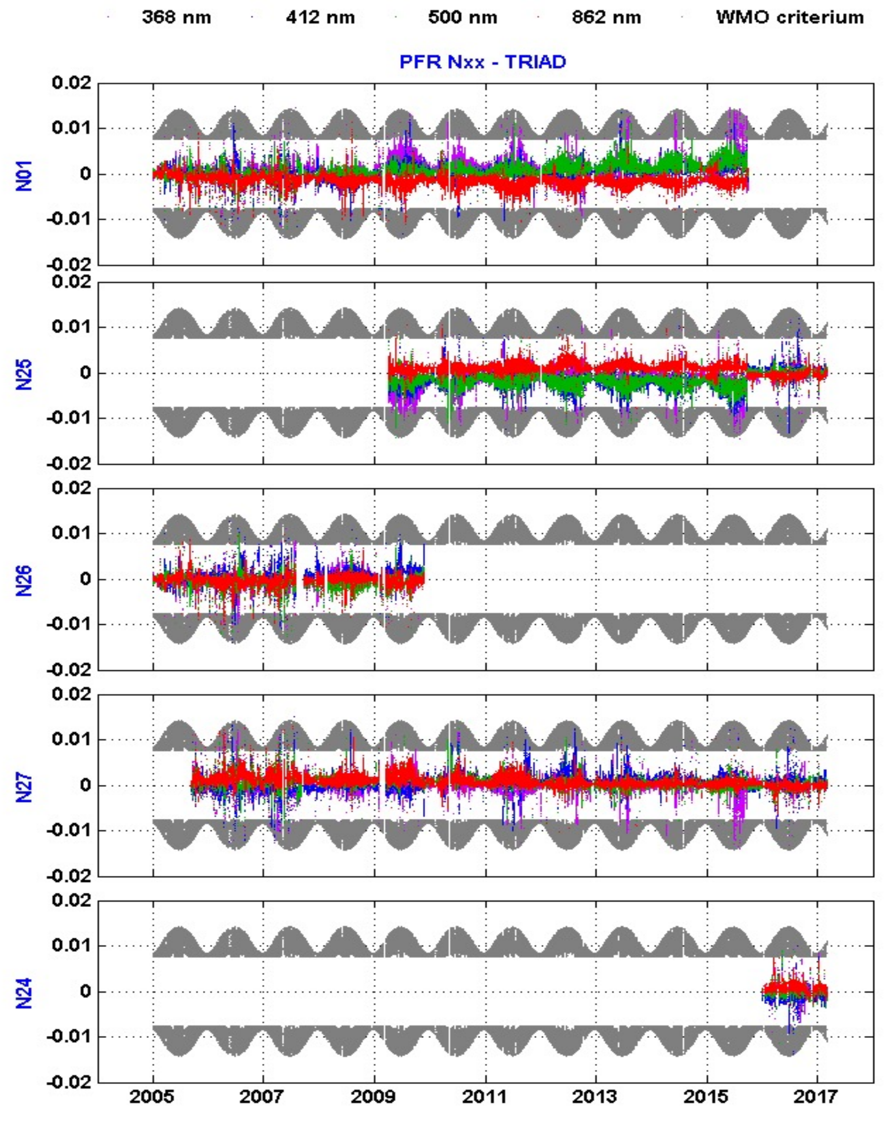
0.005: post processing and instrumental uncertainty sources
0.01/m: 1% calibration uncertainty

$$\Delta\tau \approx \frac{1}{m}\left(\frac{\Delta I_0}{I_0}\right)$$

2005-2019 99.5% of 1 minute data within U95

Triad 2005-2019





Kazadzis et al., 2018

Homogenization

- Organization of campaigns and comparisons

What to compare ?

WMO Report No. 162 discusses criteria for AOD quality

“The ability to trace calibration to a primary reference(s) (i.e. traceability) not currently possible based on physical meas. systems. Hence, traceability based on AOD difference criteria”

Compare synchronous AODs

WMO rep. 162, 2005

Homogenization

- Organization of campaigns and comparisons

What to compare ?

$$I(\lambda,\theta,r) = \frac{I_0(\lambda)}{r^2} * e^{-\left[\delta_R * m_R(\theta) + \delta_\tau * m_\tau(\theta) + \delta_G * m_G(\theta)\right]}$$

$$AOD = \delta_\tau(\lambda) = \frac{\ln\left(\frac{I_0(\lambda)}{I * r^2}\right) - \frac{p}{p_0} m_R(\theta)\delta_R(\lambda) - m_{O3}(\theta)\delta_{O3}(\lambda) - m_{NO2}(\theta)\delta_{NO2}(\lambda)}{m_\tau(\theta)}$$

WMO Report No. 162 discusses criteria for AOD quality

"The ability to trace calibration to a primary reference(s) (i.e. traceability) not currently possible based on physical meas. systems. Hence, traceability based on AOD difference criteria"

Compare synchronous AODs

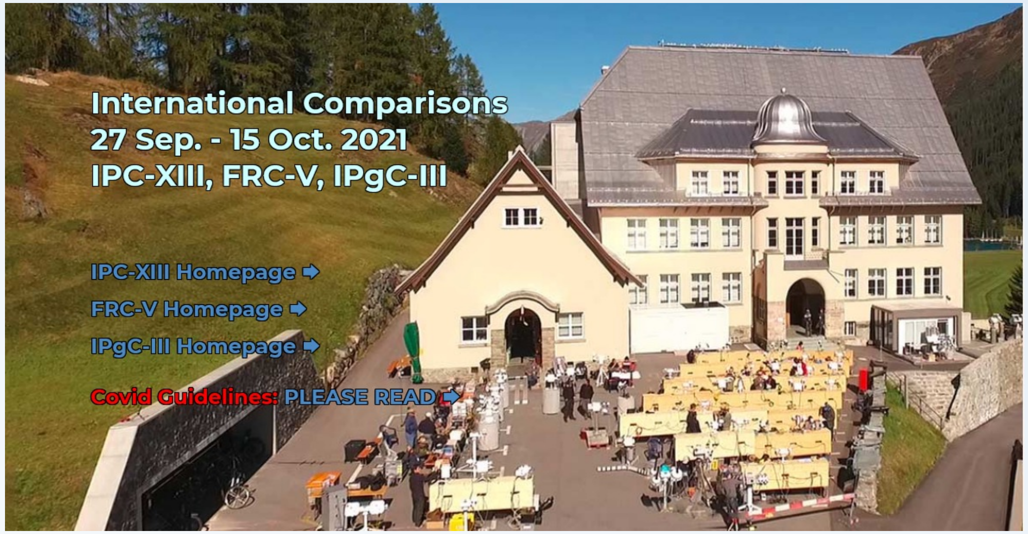
Differences

- Algorithms
- NO_2, O_3, Rayleigh inputs
- Calibration
- Technical, e.g. FOV
- Cloud flagging

Filter-Radiometer Comparison

- **5th Filter-Radiometer Comparison (FRC-V)**
- 13th International Pyrheliometer Comparison (IPC-XIII)
- 3nd International Pyrgeometer Comparison (IPgC-III).

organized by the World Radiation Center (WRC) on behalf of the World Meteorological Organization (WMO).



2000

2005

2010

2015

History

2000: FRC – I

Instrument signal comparison

7 wavelengths, 17 radiometers, 1 day measurements

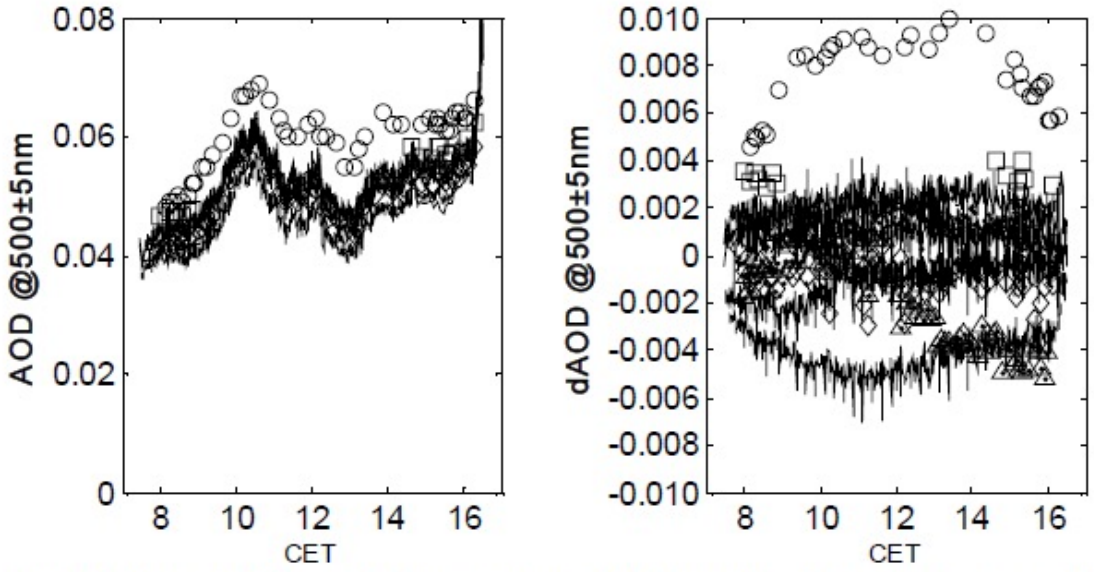
common processing → ∂δ≈0.016 @ 500nm (N=8)

2005: FRC – II AOD results

12 instruments at wavelengths 500±3nm & 865±5nm,

specific processing

comparison according to WMO recommendations (2004)



History

2010: FRC – III AOD results

17 instruments at wavelengths 500±3nm & 865±5nm,

Individual processing

FRC-IV 2015

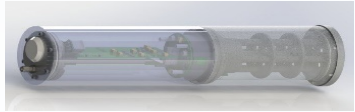
AOD Comparison at wavelengths 367±5nm, 412±5nm, 500±3nm & 865±5nm, Ångström exponents

specific processing by participants comparison according to WMO recommendations (2004)

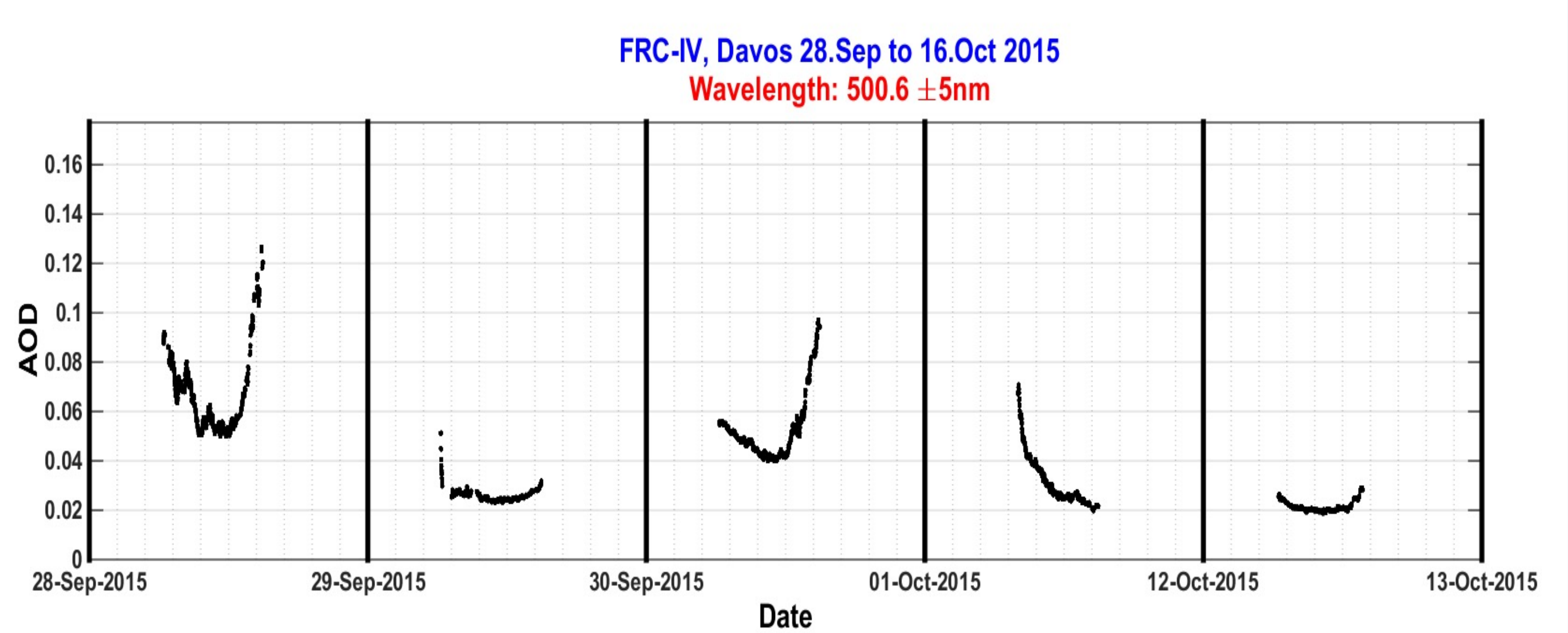
30 Instruments, 12 countries

2021

33 INSTRUMENTS – 15 GROUPS – 12 COUNTRIES

PFR	CIMEL	PSR	POM-2	SPO2	G-Pho	Microtops
WORCC Triad-CH (3) SMHI-SE DWD-DE (2) PMOD-CH (3) +new MeteoSwiss-CH NIMS-KO UIIMP (AT)	PMOD-CH IZANA-ESP Valliadolid-ESP MetoSwiss-Ch Un. Lille (FR) Carsnet (CN)	DWD-DE (2) PMOD-CH (3) BOM-AU (1)	DWD-DE CNR-IT JMA-JP K. ABDALA-SA	BMa-AU BMb-AU	GPHO-CN	MIC-AR
 						
Direct sun wl: 368, 412, 500, 863 nm Fwhm: 3.8-5.4nm FOV=2.5 deg Meas: 1 minute	Direct sun wl: 340, 379, 440, 500, 670, 870, 1064 nm Fwhm: 10 nm FOV=1.2 deg Meas: ~10 minute	Direct sun spec wl: 320-1000 nm Fwhm: 1.5-6 nm FOV=1.5 deg Meas: ~10 sec	Direct sun spec wl: 315, 340, 380, 400, 500, 675, 870, 940, 1020, 1627, 2200 nm Fwhm: 10 nm FOV=1 deg Meas: 1 min	Direct sun spec wl: 368, 412, 502, 675, 778, 812, 862nm Fwhm: 5 nm FOV=2.4 deg Meas: 1 min	Direct sun spec	Direct sun spec wl: 6 filters Fwhm: 10 nm FOV=2.5 deg Meas: 1 min

2015 - AOD variability



samples at 500nm (PFR, POM-2, SPO, MFRSR, PSR, SIM: 1100-2000, CIMEL: ~300, 750, MIC: 350)

Duration ≥5 days OK

AOD500 within 0.040 ÷ 0.200 OD .. OK

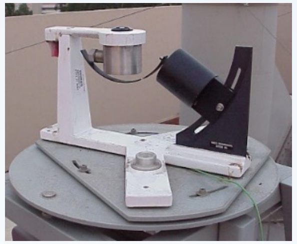
U95: dAOD ≤ 0.005 + 0.01/m

FRC/Participating Instruments - 2015

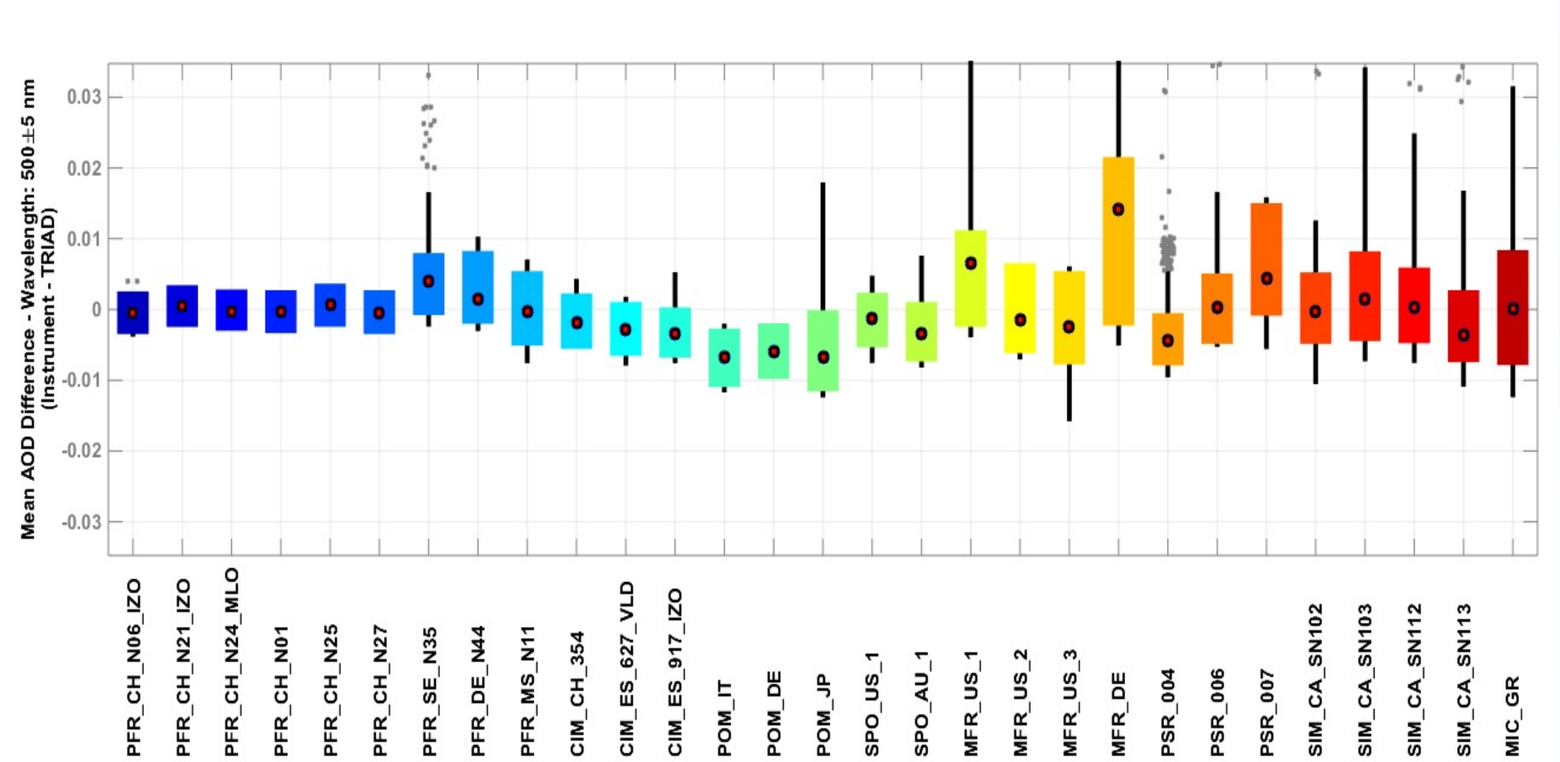
30 instruments – 15 groups – 12 countries

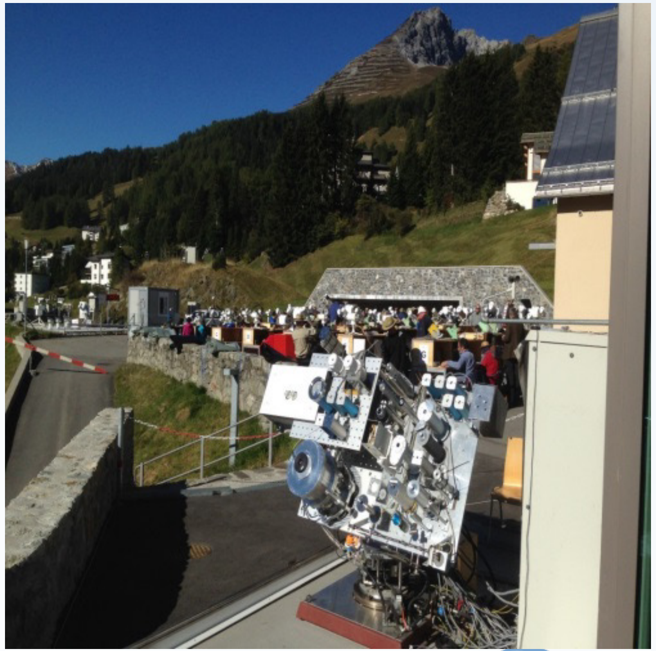
PFR	CIMEL	MFRSR	PSR	POM-2	SPO2	SSIM	Microtops
GAW-PFR	AERONET-EU	SURFRAD	DWD	SKYNET	AU-NET		





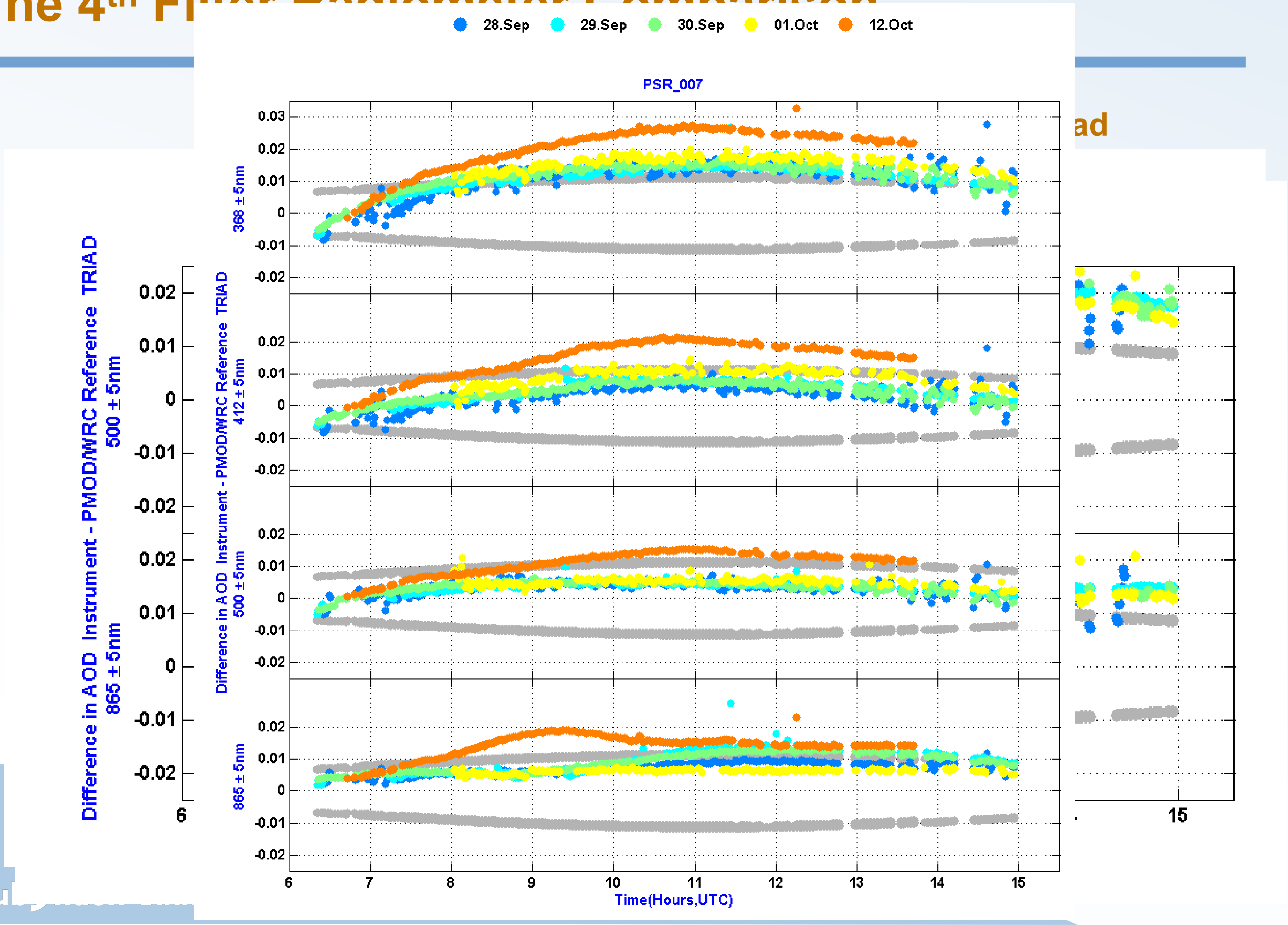






Kazadzis et al., 2018

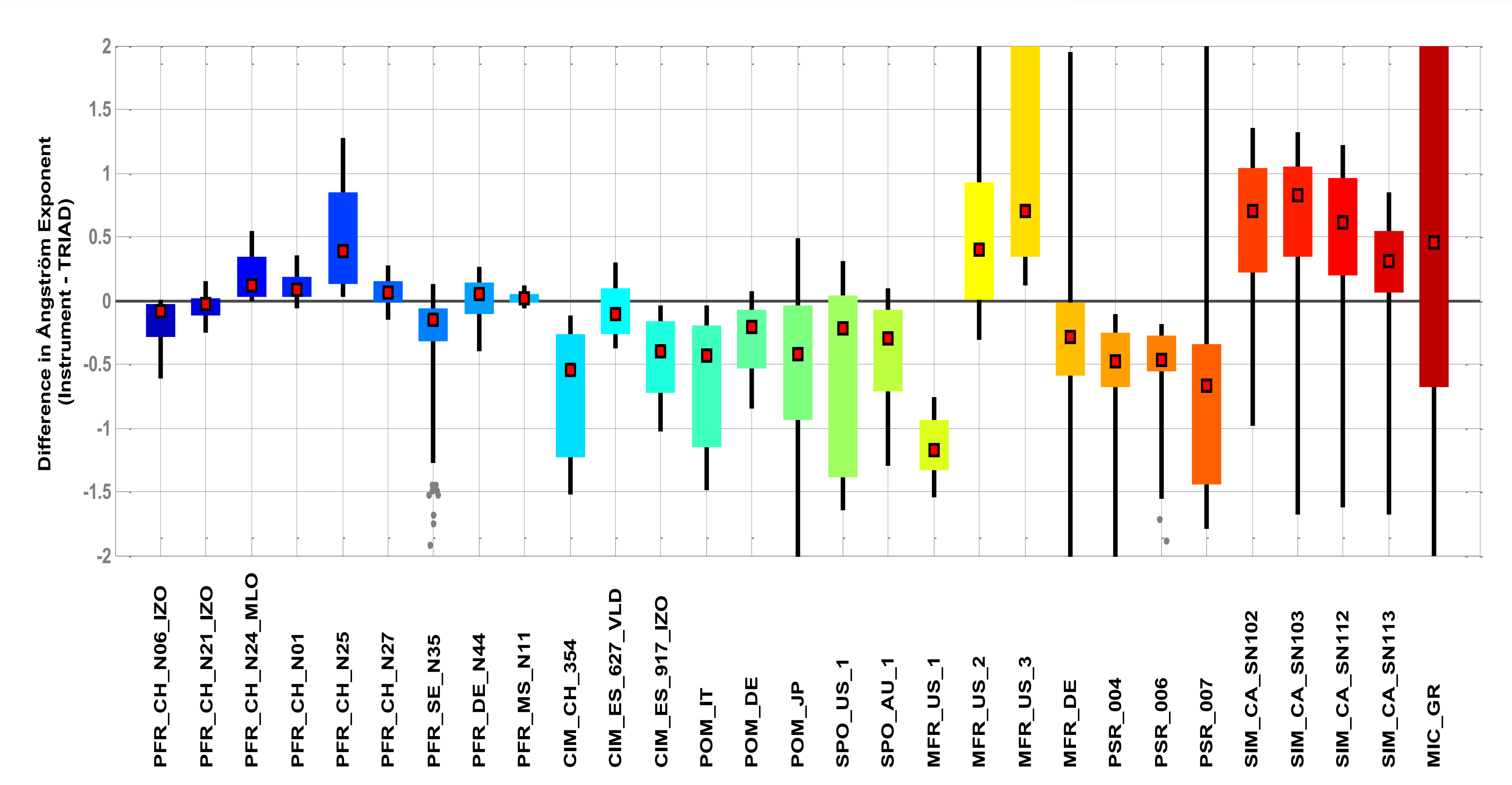
The 4th Filter Radiometer Comparison



grau

pmod wrc

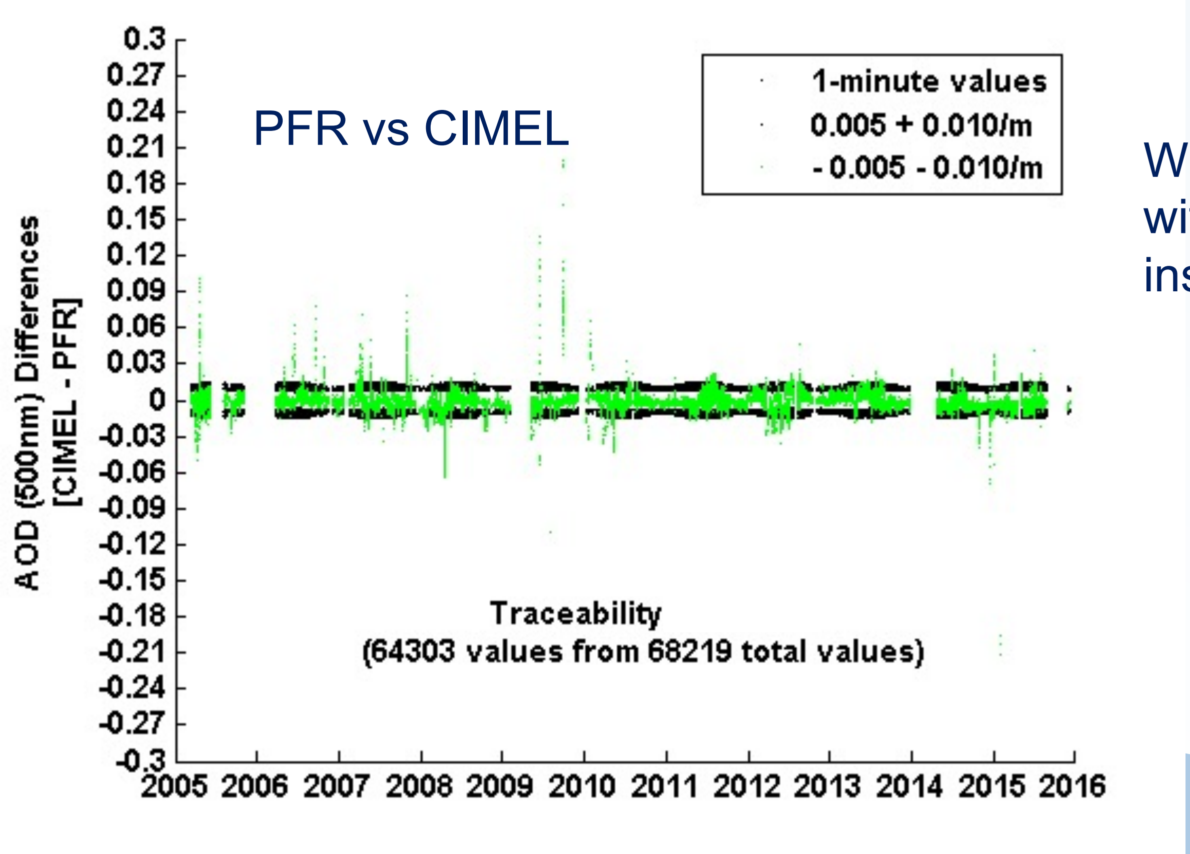
Ångström Exponents



Long term measurements at CIMEL “reference” locations: Izana, Spain (AEMET)

Long term AOD CIMEL / PFR analysis:

60K-70K synchronous AODs



WMO-U95 criterion “95% within the limits for reference instruments”

380 nm	440 nm	500 nm	865 nm
92.3%	95.1%	96.2 %	97.8%

Differences:

- Processing algorithms
- NO_2, O_3, pressure inputs
- Small wavelength/filter differences
- Instrument issues

Cuevas et al., 2019

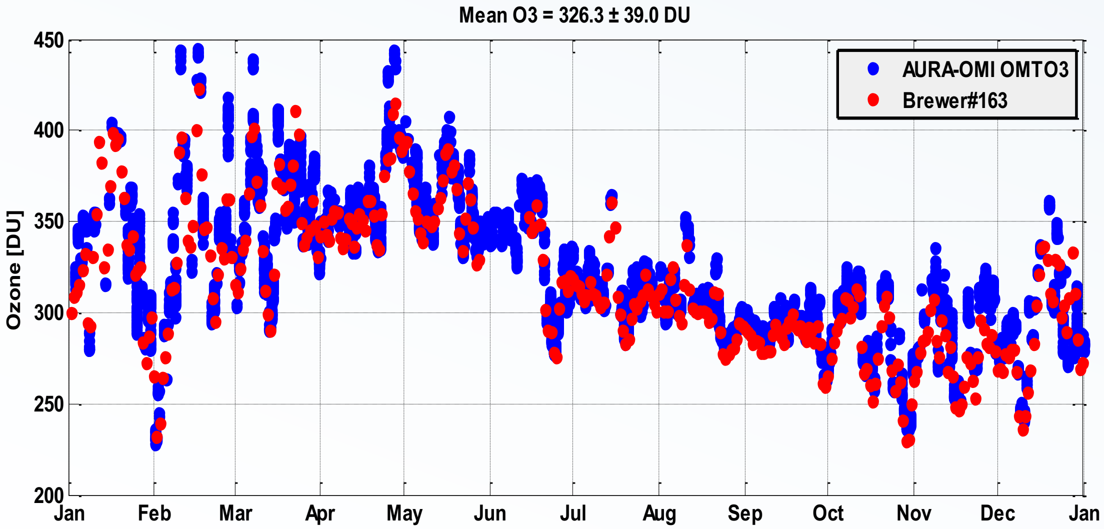
pmod wrc

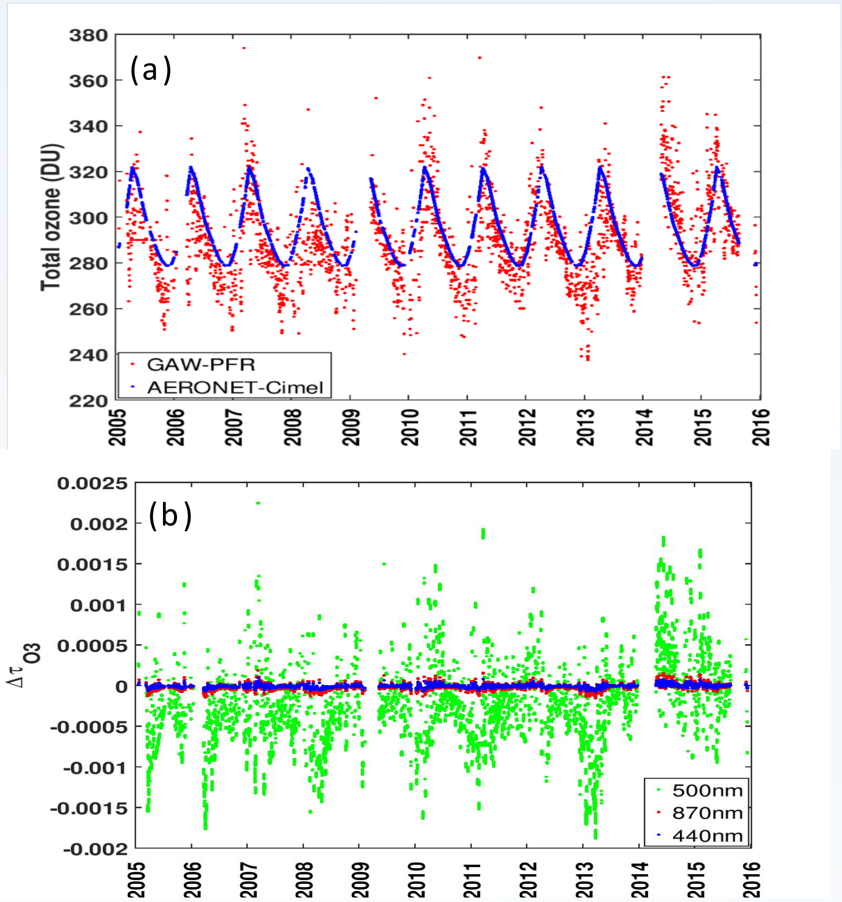
Long term homogenization measurements

Uncertainties / Differences

AOD processing: Ozone $\tau_\lambda = \tau_{O3} + \tau_{aer} + \tau_{Ray} + \tau_{clouds} + \tau_{NO_2}$

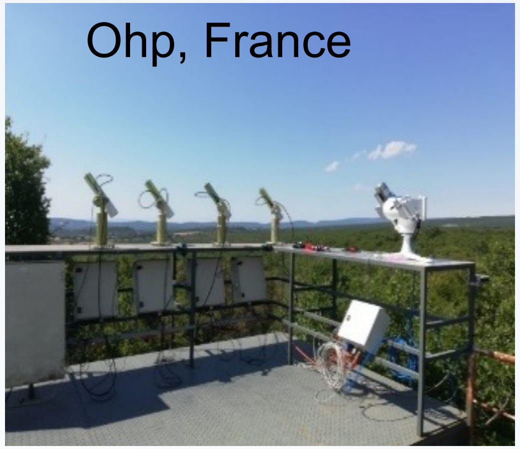
- *Climatology*
- *Satellite*
- *Measurement*

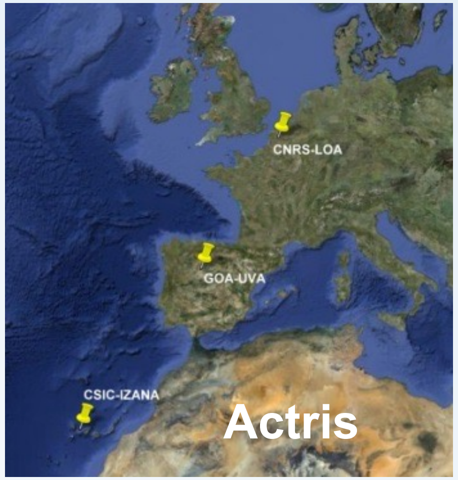


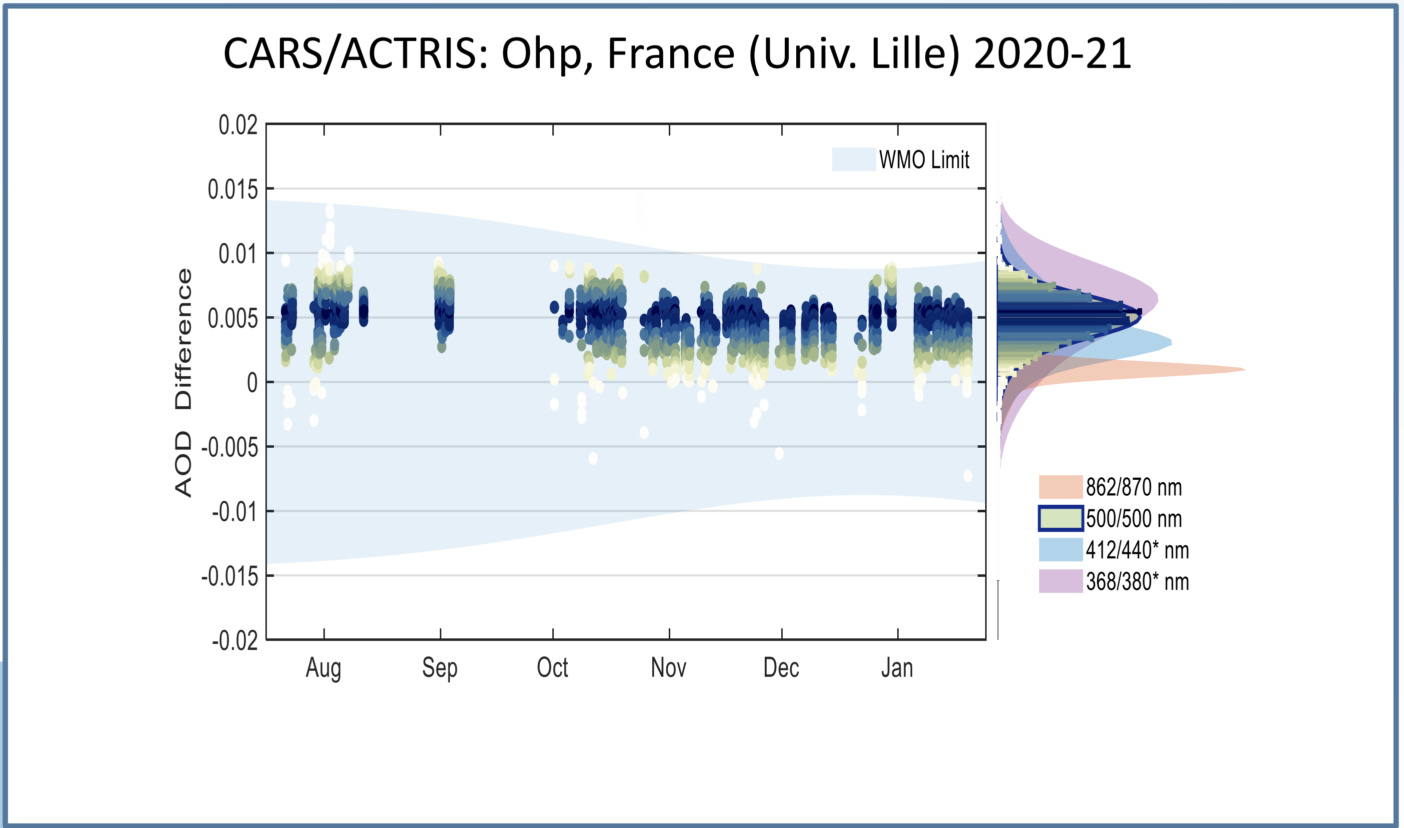


Cuevas et al., 2019

Actris European infrastructure & WMO



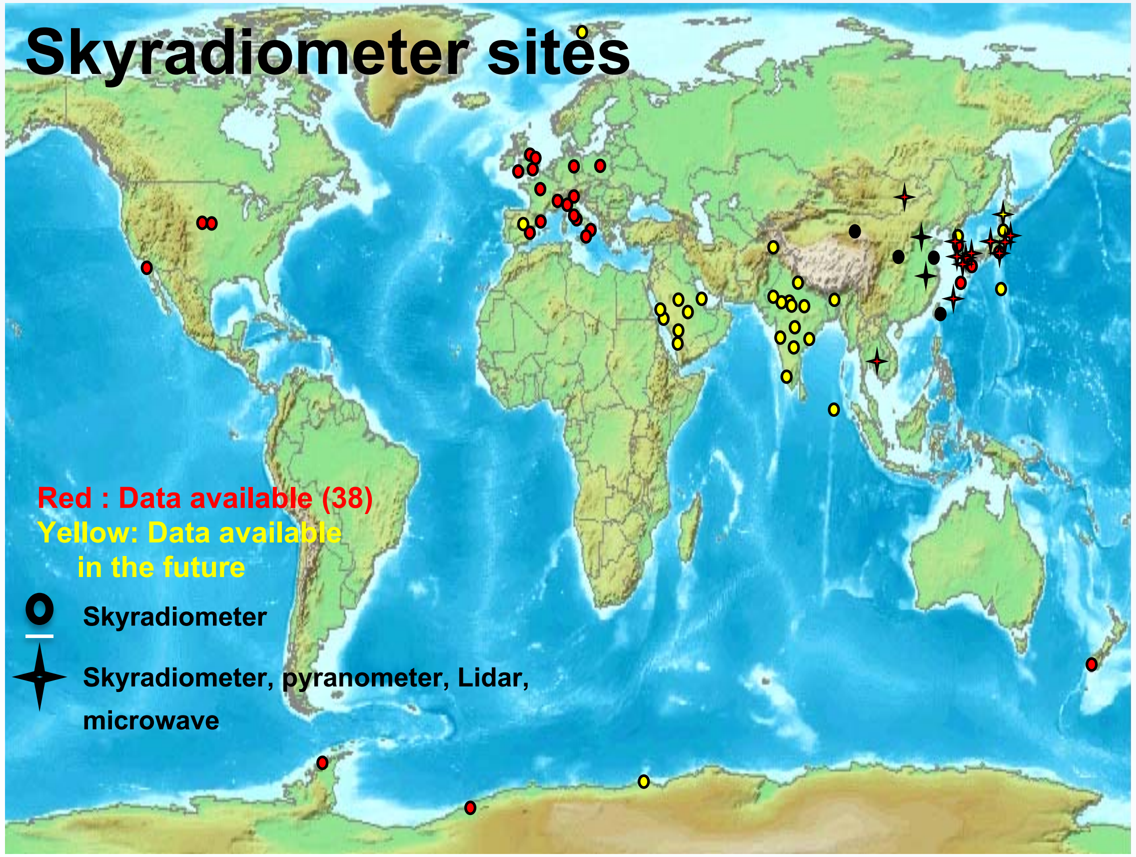




ACTRIS
Calibration Aerosol Remote Sensing

Establish traceability of AOD measurements within CARS/ACTRIS to the primary WMO AOD reference

WMO and Skynet



MoU Comparison with reference instr.
Measurements at reference/calibration sites

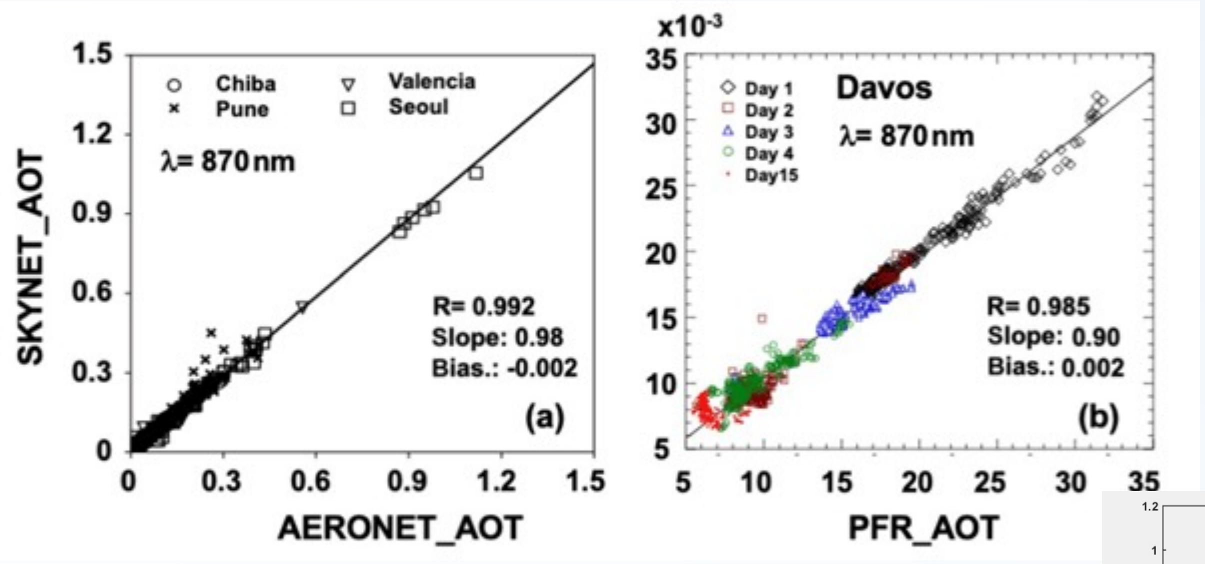
MoU with CNR, Italy for Skynet reference traceability to WORCC
(WMO-SAG aerosol: Skynet to WDCA)

2015 FRC-4 at Davos
2016 Chiba/Japan and Valencia/Spain
2017 Davos – WORCC
2017-18 Quatram camp., Rome (IT)
2018 Davos - WORCC
2018-19 Quatram camp. 2, Rome (IT)

2021 Rome
2021 FRC 5 Davos

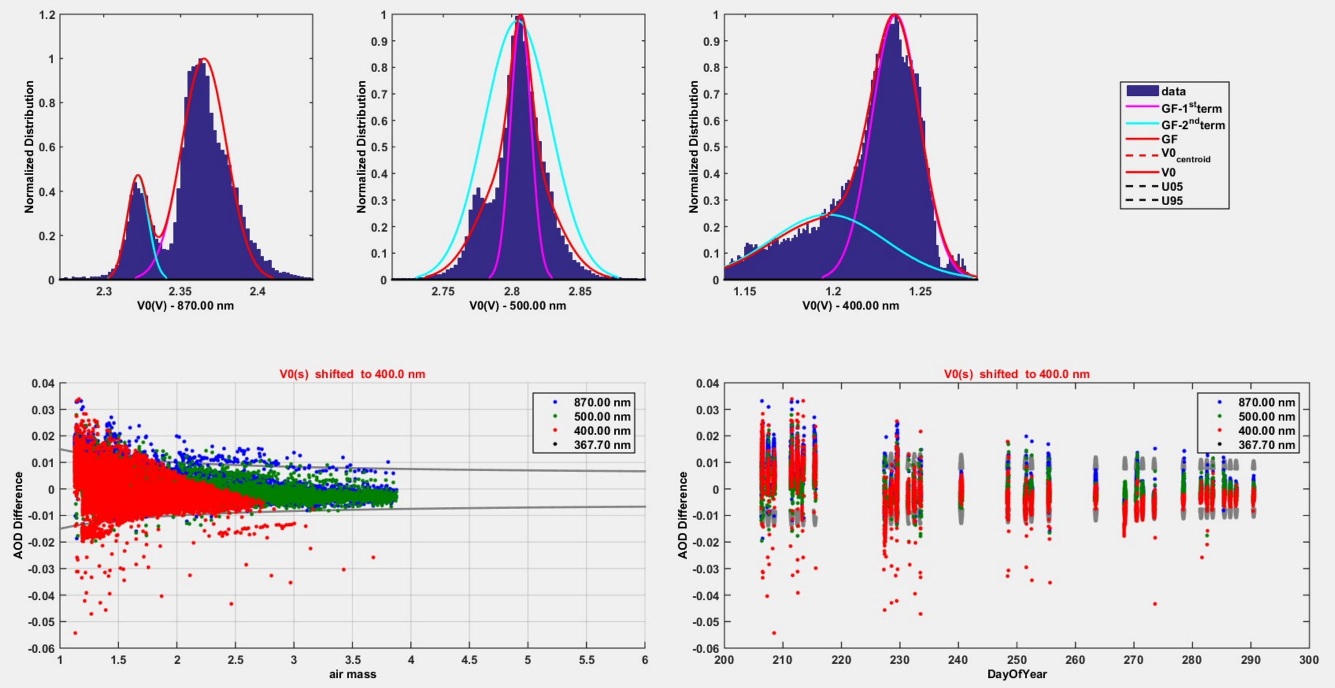
WMO and Skynet

Nakajima et al., 2020



Chiba, Japan 2017

$$I_\lambda = I_\lambda^0 * e^{-\tau_\lambda m}$$

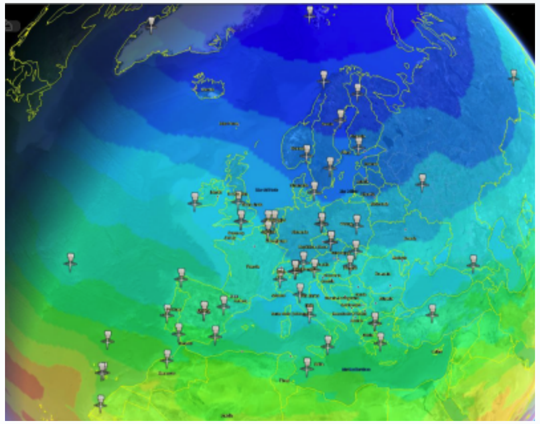


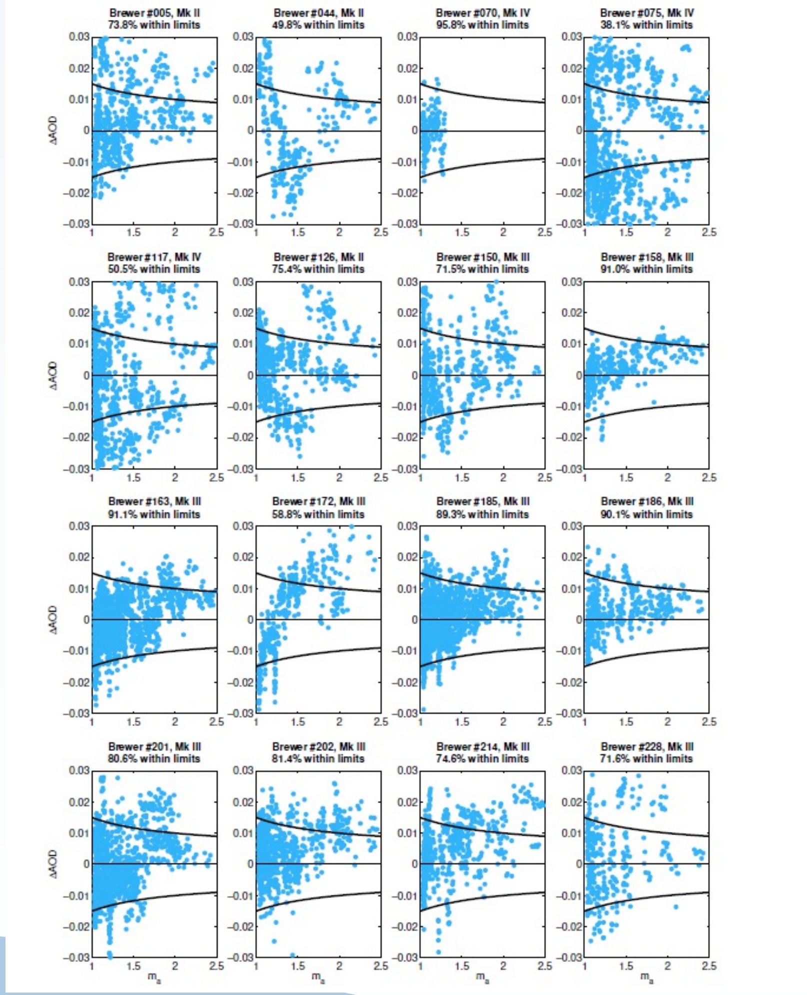
- Quatram campaign: Rome

European brewer Network

Development of a traveling UV-PFR reference for calibrating Brewer instruments

Participation in 10th Regional Brewer Calibration Campaign, Huelva, Spain, 2015





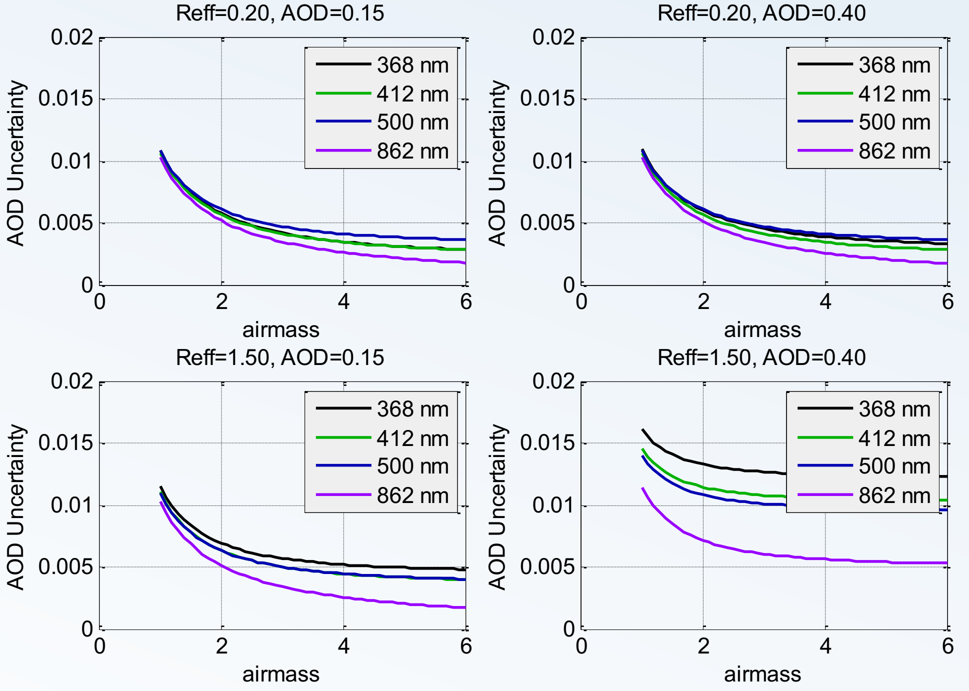
16 Brewers vs UV-PFR,
AOD comparison
at 313.5 nm,

Ozone !!

Solano et al., 2018
Carlund et al., 2017

Uncertainty estimation

Source	Uncertainty	Impact on	δAOD (wavelengths(nm))
1. Measurement & tracking	0.0025	Meas. Voltage/AOD	0.0025/ m
2. calibration Uncertainty	<0.01	AOD	0.01/ m
3. Pressure	<±5hPa	τ_{ray}	0.0002 (862) – 0.0025(368)
4. NO_2	±0.05nm	τ_{NO2}	0(862) - 0.003(368)
5. Ozone	± 10DU	τ_{O3}	0 (all) - 0.0003 (500)
6. Field of View	Depending on aerosol type and AOD	Meas. Voltage/AOD	0 – 0.12 (368, AOD=0.4, eff. Radius = 1.5μm)



Instruments: possible problems !!

Quality control and assurance procedures

Recalibration* (When ?)

Solar Pointing tolerance and link with the initial calibration (0.05 deg)

AOD retrieval inputs: e.g. Ozone, pressure, e.t.c.

Cloud flagging algorithm

Temperature

Wavelength crossing checks (negative AEs ?)

Ångström paremeter threasholds

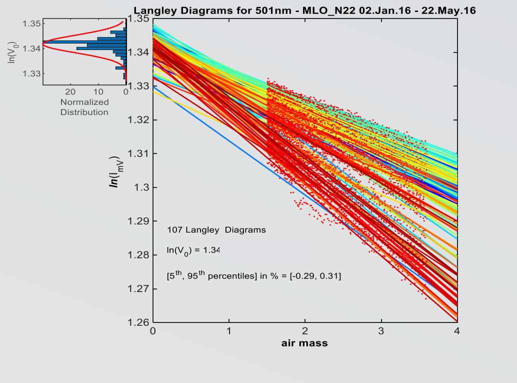
Visual inspections

Metrology of Aerosol Optical Properties

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

field calibrations
Langley
Relative (signals)
Calibration

Langley : Io= Vo , I=Signal (V)

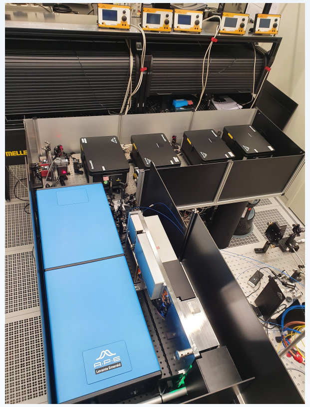


$$I_\lambda = I_\lambda^0 * e^{-\tau_\lambda m}$$

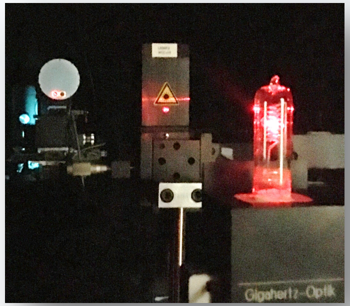
Volts

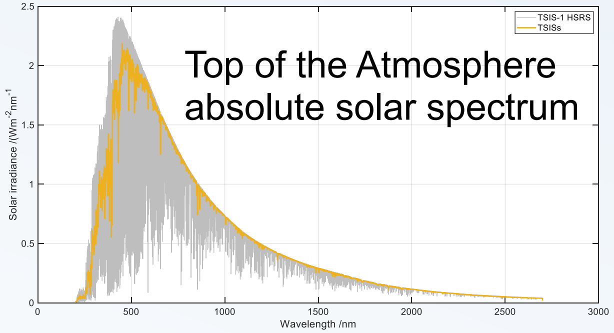
$$m = 0$$

To **SI traceable absolute calibration** of the PFR
using in addition a Top of the Atmosphere absolute solar spectrum



PTB German metrology Institute





Top of the Atmosphere absolute solar spectrum

$$I_\lambda = I_\lambda^0 * e^{-\tau_\lambda m}$$

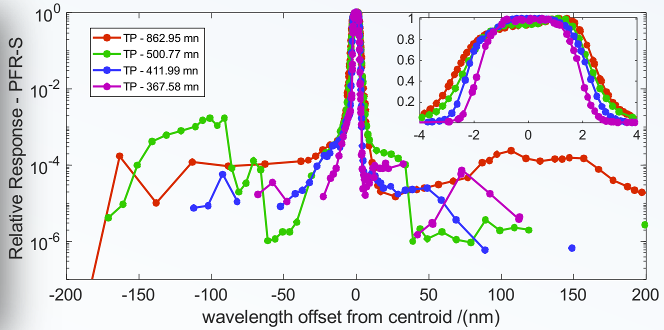
W/m²*nm

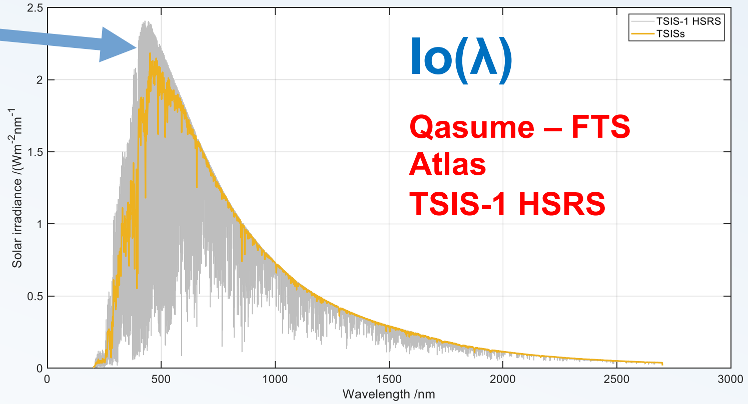
Metrology for Aerosol optical properties / MAPP project

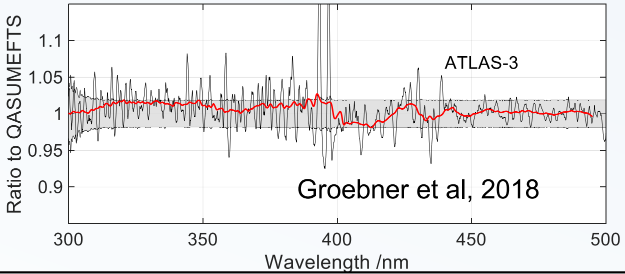
$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda m}$$

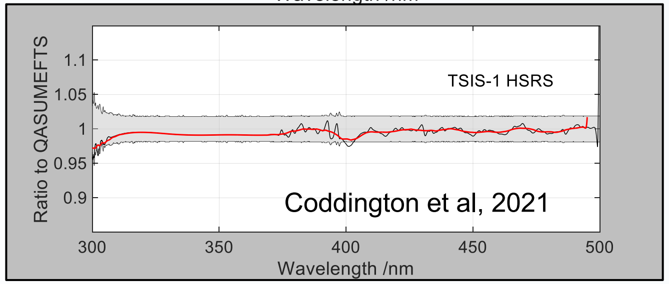
$$AOD = \frac{\ln {}^{I_0}/_{I}}{m} - \sum_i \tau_{att(i)} m_{att(i)} / m_a$$

TULIP setup PTB





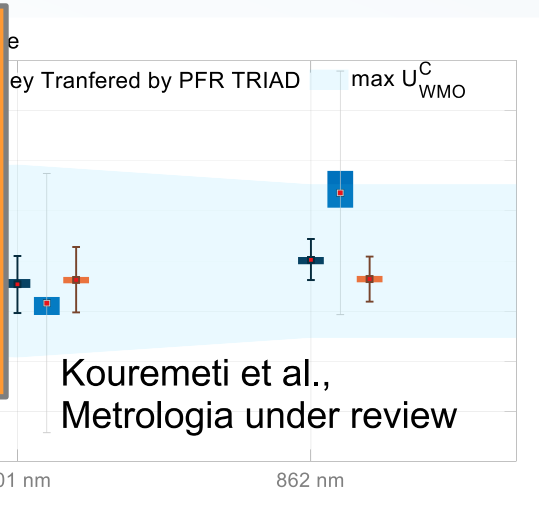




Achieved:

- ✓ **Calibrations with U< 0.5%**
- ✓ **ETS Consistency with Calibration <1%**
  for TSIS & QASUME-FTS

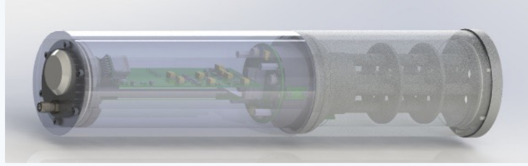
Δ_{AOD} ~ 0.005 ±0.005

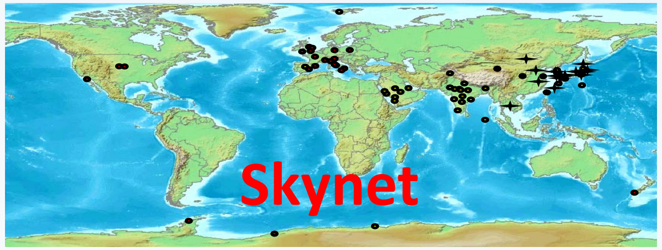


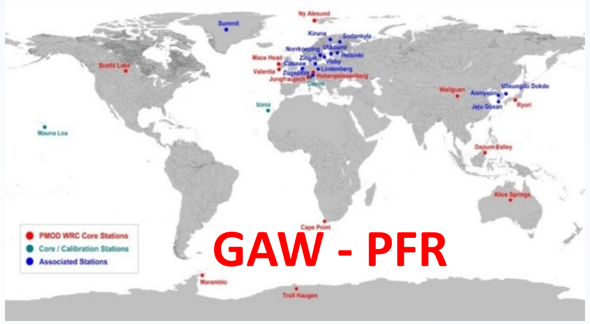
Kouremeti et al.,
Metrologia under review

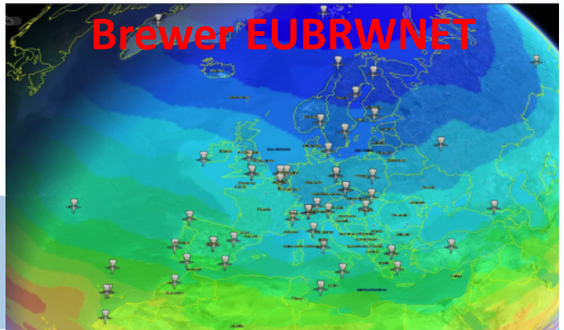
World aerosol Optical depth Research and calibration Center vs global networks

Precision Filter Radiometer (PFR)
Sun-photometer
WMO reference

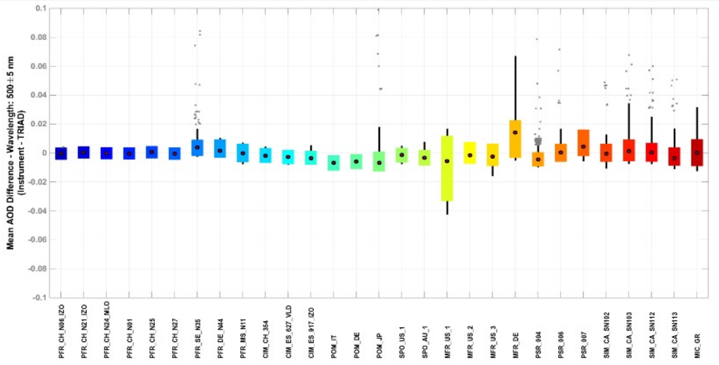








Filter Radiometer Comparisons (2000-2021)



World Reference AOD triad

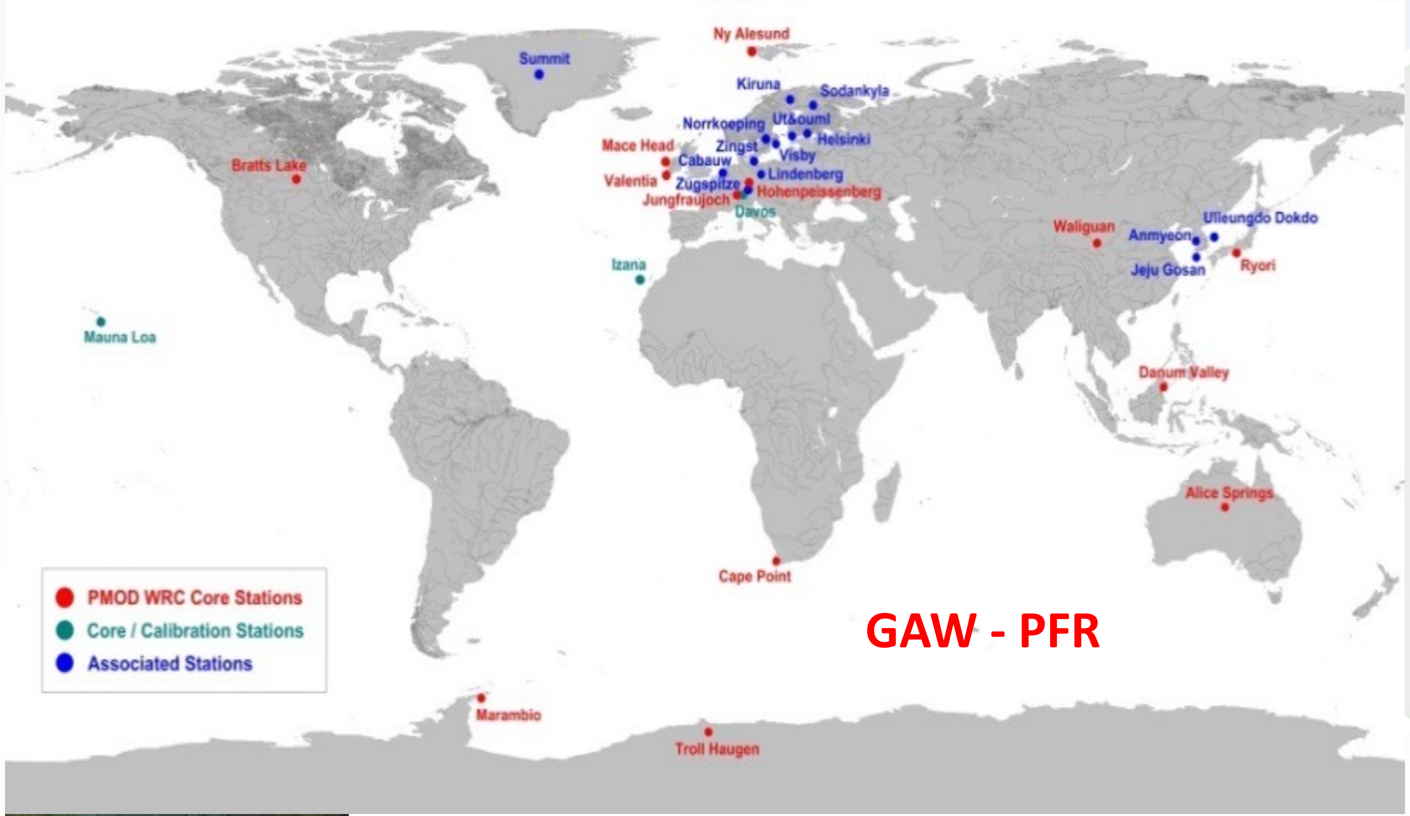
Mauna Loa, Hawaii, USA

Izaña, Tenerife, Spain

Davos, CH PFR triad

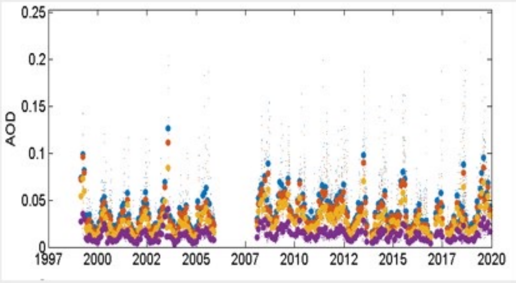
Aerosol Optical Depth / WMO-Global Atmosphere Watch network GAWPFR

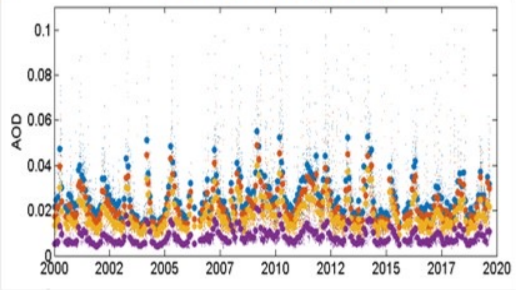
~30 stations, operated and maintained by PMOD/WRC.



Long term multi-wavelength AOD measurements:

Jungfraujoch (Switzerland) and **Mauna Loa (USA)**





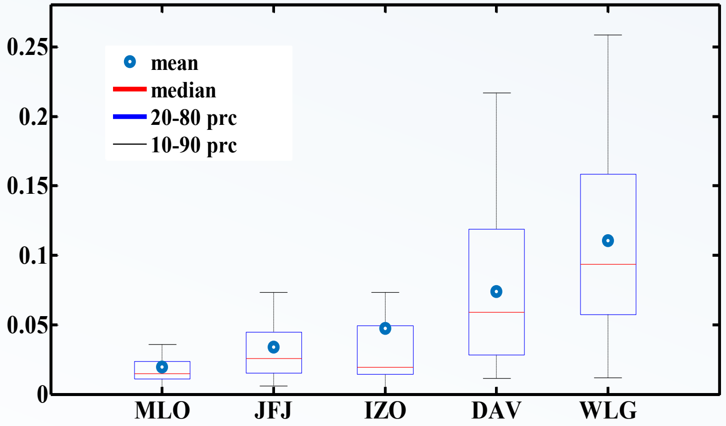
>20 years data sets

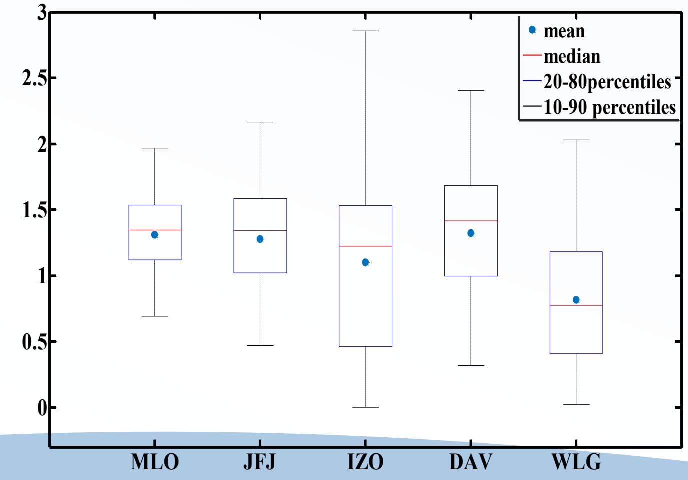
graubünden Education and Research.

pmod wrc

The GAW-PFR Network

Addressing atmospheric composition on all scales: from global and regional to local and urban.





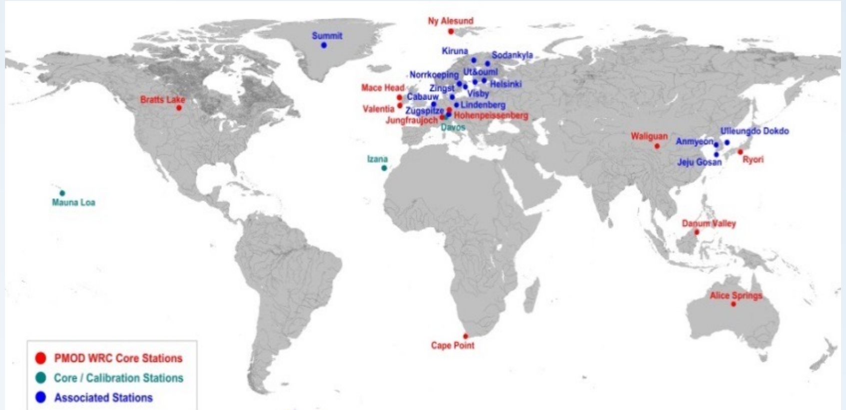
Mauna Loa
(USA) -3.4Km,

Jungfraujoch
(Switzerland) - 3.6Km,

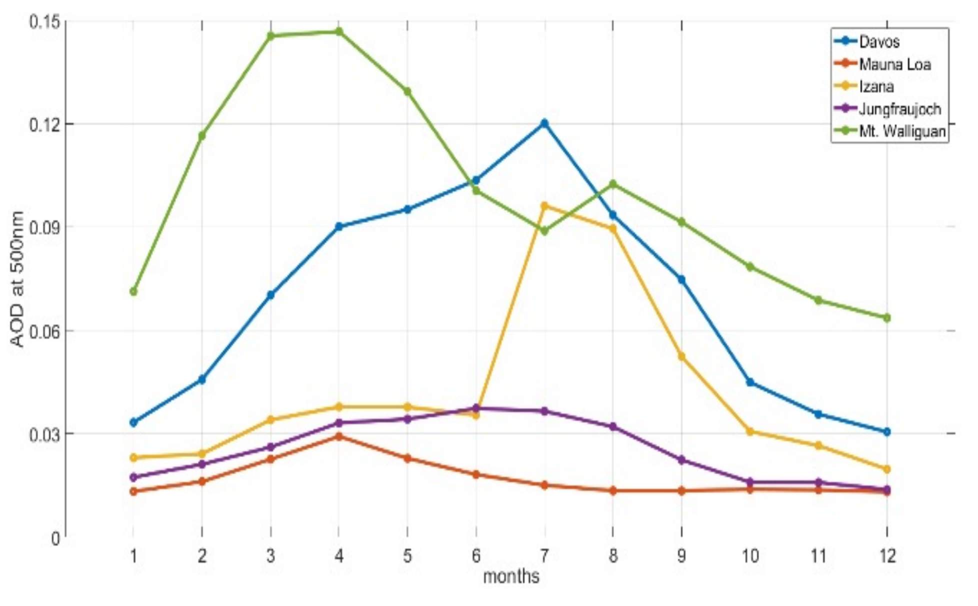
***Izana** (Spain)*
-2.3Km,

***Davos** (Switzerland)*
-1.5Km,

***Mount Walliguan** (China)*
-3.8Km



GAW-PFR
Network for long term AOD measurements

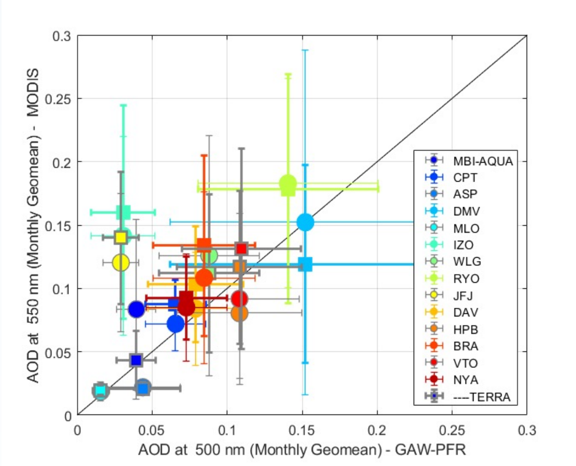


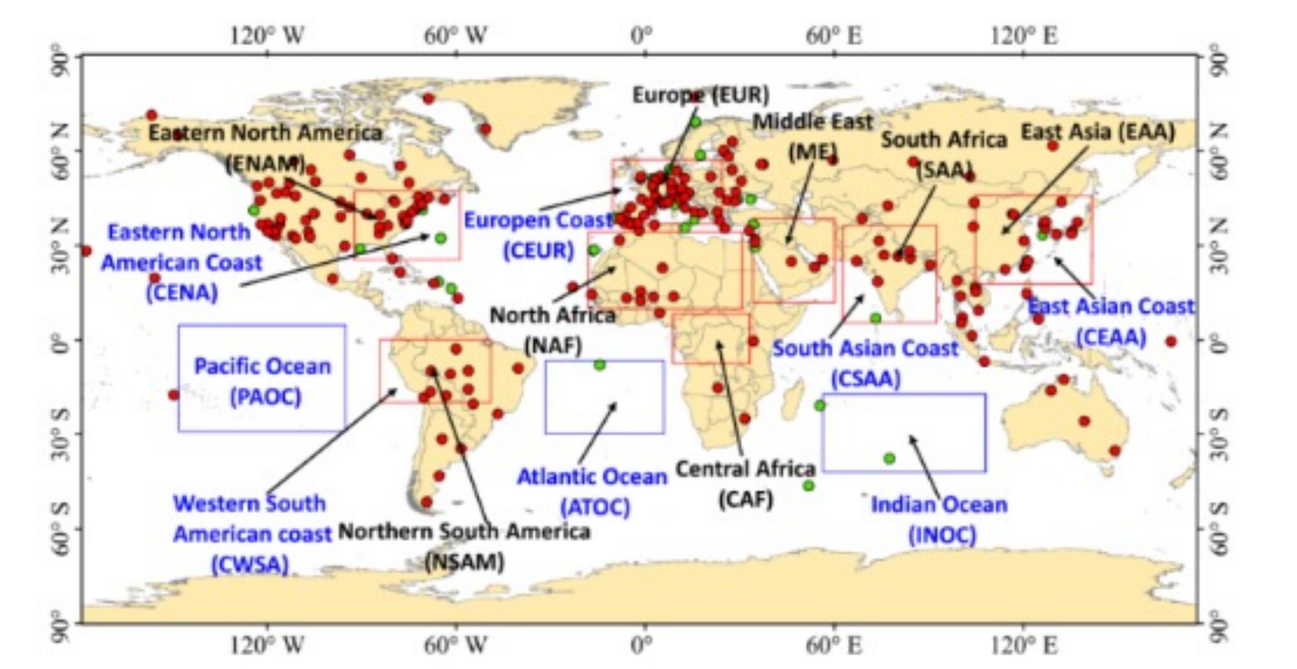
graubünden Education and Research.

pmod wrc

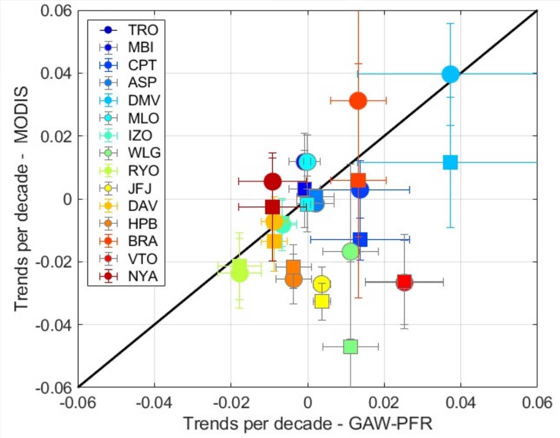
Why do we need homogenized surface based measurements of AOD ?

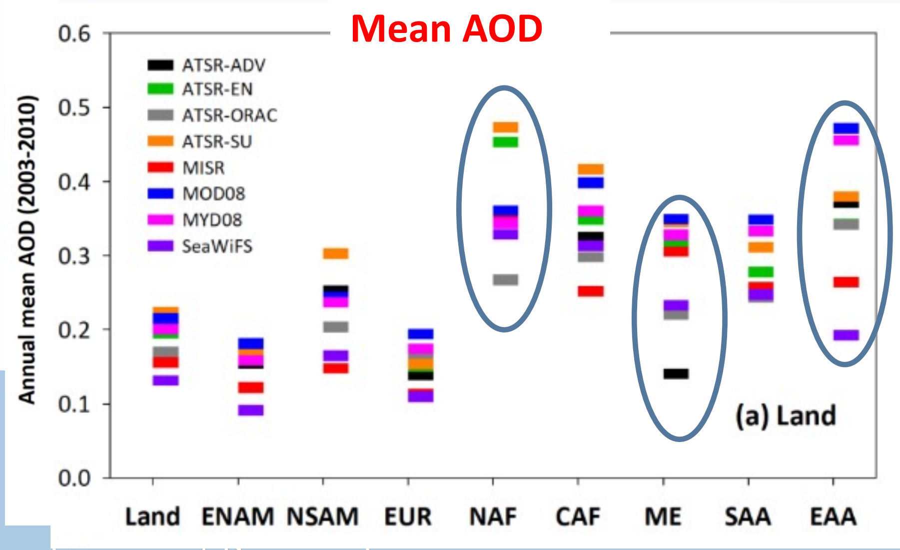
comparison

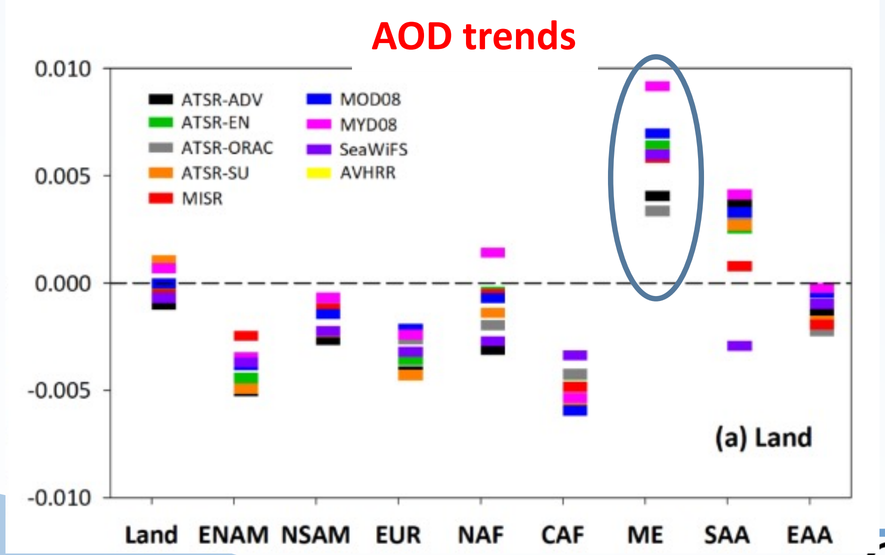




trends







Wei et al., 2018

Summary and thoughts

Homogenization activities for AOD

Aim: Try to have global AOD surface based measurements with minimum uncertainties, independently of the instrument/network used.

Harmonize: Calibration, algorithms, input options, instrument characterization, maintenance and technical characteristics

Organize experimental field and lab based campaigns

Try to link calibration of AOD with SI units related traceability

Carefully estimate instrument / network uncertainties

Find common statistical ways to correctly present AOD trends

Expand measurement capabilities (e.g. spectral measurements)

Thank you

Stelios.kazadzis@pmodwrc.ch

ACTRIS
Exploring the Atmosphere

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

WORLD METEOROLOGICAL ORGANIZATION
Weather · Climate · Water

graubünden Education and Research.

pmod wrc

1. Nakajima, T., Campanelli, M., Che, H., Estellés, V., Irie, H., Kim, S.-W., Kim, J., Liu, D., Nishizawa, T., Pandithurai, G., Soni, V. K., Thana, B., Tugjsurn, N.-U., Aoki, K., Go, S., Hashimoto, M., Higurashi, A., Kazadzis, S., Khatri, P., Kouremeti, N., Kudo, R., Marenco, F., Momoi, M., Ningombam, S. S., Ryder, C. L., Uchiyama, A., and Yamazaki, A.: An overview of and issues with sky radiometer technology and SKYNET, Atmos. Meas. Tech., 13, 4195–4218, https://doi.org/10.5194/amt-13-4195-2020, 2020.
2. Cuevas, E., Romero-Campos, P. M., Kouremeti, N., Kazadzis, S., Räisänen, P., García, R. D., Barreto, A., Guirado-Fuentes, C., Ramos, R., Toledano, C., Almansa, F., and Gröbner, J.: Aerosol optical depth comparison between GAW-PFR and AERONET-Cimel radiometers from long-term (2005–2015) 1 min synchronous measurements, Atmos. Meas. Tech., 12, 4309–4337, https://doi.org/10.5194/amt-12-4309-2019, 2019
3. Toledano, C., González, R., Fuertes, D., Cuevas, E., Eck, T. F., Kazadzis, S., Kouremeti, N., Gröbner, J., Goloub, P., Blarel, L., Román, R., Barreto, Á., Berjón, A., Holben, B. N., and Cachorro, V. E.: Assessment of Sun photometer Langley calibration at the high-elevation sites Mauna Loa and Izaña, Atmos. Chem. Phys., 18, 14555-14567, https://doi.org/10.5194/acp-18-14555-2018, 2018
4. Benedetti, A., Reid, J. S., Knippertz, P., Marsham, J. H., Di Giuseppe, F., Rémy, S., Basart, S., Boucher, O., Brooks, I. M., Menut, L., Mona, L., Laj, P., Pappalardo, G., Wiedensohler, A., Baklanov, A., Brooks, M., Colarco, P. R., Cuevas, E., da Silva, A., Escribano, J., Flemming, J., Huneeus, N., Jorba, O., Kazadzis, S., Kinne, S., Popp, T., Quinn, P. K., Sekiyama, T. T., Tanaka, T., and Terradellas, E.: Status and future of numerical atmospheric aerosol prediction with a focus on data requirements, Atmos. Chem. Phys., 18, 10615-10643, https://doi.org/10.5194/acp-18-10615-2018, 2018
5. López-Solano, J., Redondas, A., Carlund, T., Rodriguez-Franco, J. J., Diémoz, H., León-Luis, S. F., Hernández-Cruz, B., Guirado-Fuentes, C., Kouremeti, N., Gröbner, J., Kazadzis, S., Carreño, V., Berjón, A., Santana-Díaz, D., Rodríguez-Valido, M., De Bock, V., Moreta, J. R., Rimmer, J., Smedley, A. R. D., Boulkelia, L., Jepsen, N., Eriksen, P., Bais, A. F., Shirotov, V., Vilaplana, J. M., Wilson, K. M., and Karppinen, T.: Aerosol optical depth in the European Brewer Network, Atmos. Chem. Phys., 18, 3885-3902, https://doi.org/10.5194/acp-18-3885-2018, 2018.
6. Kazadzis, S., Kouremeti, N., Diémoz, H., Gröbner, J., Forgan, B. W., Campanelli, M., Estellés, V., Lantz, K., Michalsky, J., Carlund, T., Cuevas, E., Toledano, C., Becker, R., Nyeki, S., Kosmopoulos, P. G., Tatsiankou, V., Vuilleumier, L., Denn, F. M., Ohkawara, N., Ijima, O., Goloub, P., Raptis, P. I., Milner, M., Behrens, K., Barreto, A., Martucci, G., Hall, E., Wendell, J., Fabbri, B. E., and Wehrli, C.: Results from the Fourth WMO Filter Radiometer Comparison for aerosol optical depth measurements, Atmos. Chem. Phys., 18, 3185-3201, https://doi.org/10.5194/acp-18-3185-2018, 2018.
7. Kazadzis, S., Kouremeti, N., Nyeki, S., Gröbner, J., and Wehrli, C.: The World Optical Depth Research and Calibration Center (WORCC) quality assurance and quality control of GAW-PFR AOD measurements, Geosci. Instrum. Method. Data Syst., 7, 39-53, https://doi.org/10.5194/gi-7-39-2018, 2018.
8. Carlund, T., Kouremeti, N., Kazadzis, S., and Gröbner, J.: Aerosol optical depth determination in the UV using a four-channel precision filter radiometer, Atmos. Meas. Tech., 10, 905-923, doi:10.5194/amt-10-905-2017, 2017.
9. Kazadzis, S., Raptis, P., Kouremeti, N., Amiridis, V., Arola, A., Gerasopoulos, E., and Schuster, G. L.: Aerosol absorption retrieval at ultraviolet wavelengths in a complex environment, Atmos. Meas. Tech., 9, 5997-6011, doi:10.5194/amt-9-5997-2016, 2016.
10. Gkikas, A., Proestakis, E., Amiridis, V., Kazadzis, S., Di Tomaso, E., Tsekeri, A., Marinou, E., Hatzianastassiou, N., and Pérez García-Pando, C.: ModIs Dust AeroSol (MIDAS): a global fine-resolution dust optical depth data set, Atmos. Meas. Tech., 14, 309–334, https://doi.org/10.5194/amt-14-309-2021, 2021.

Assessment of AOD Quality

WMO Report No. 162 (2005) discusses criteria for AOD quality

Compare AODs

- an inter-comparison or co-location traceability will be established if AOD difference between networks is within specific limits
- Inter-comparisons should be long enough such that:
  - a) ≥ 1000 coincident AOD data points
  - b) Minimum 5 sunny days
  - c) AOD (500 nm) ~ 0.040 - 0.200
- For traceability, 95% of AOD difference should lie within:

  $U_{95} < \pm(0.005 + 0.010/airmass)$