Aerosol optical depth ground-based sensors, homogenization activities between different networks

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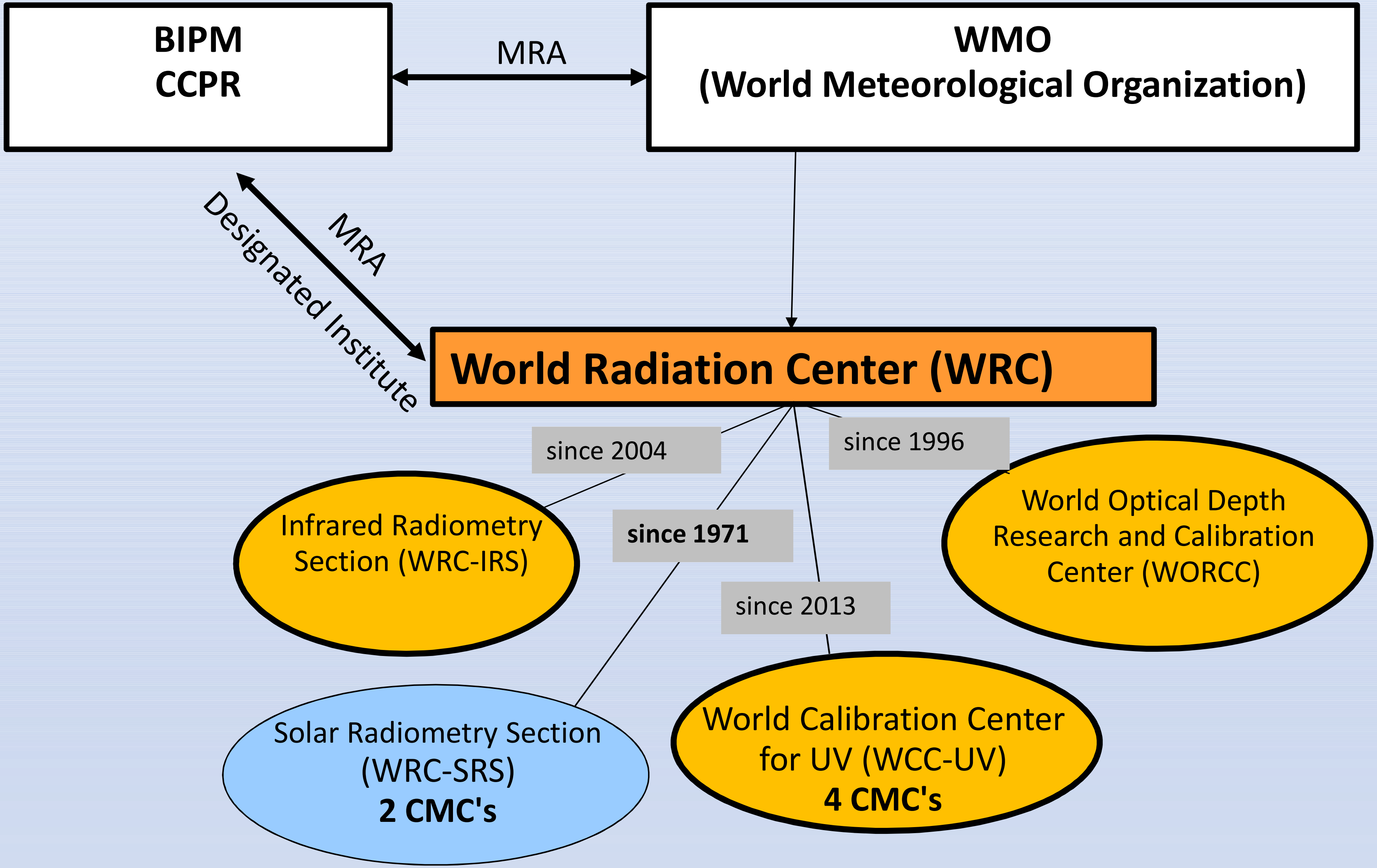
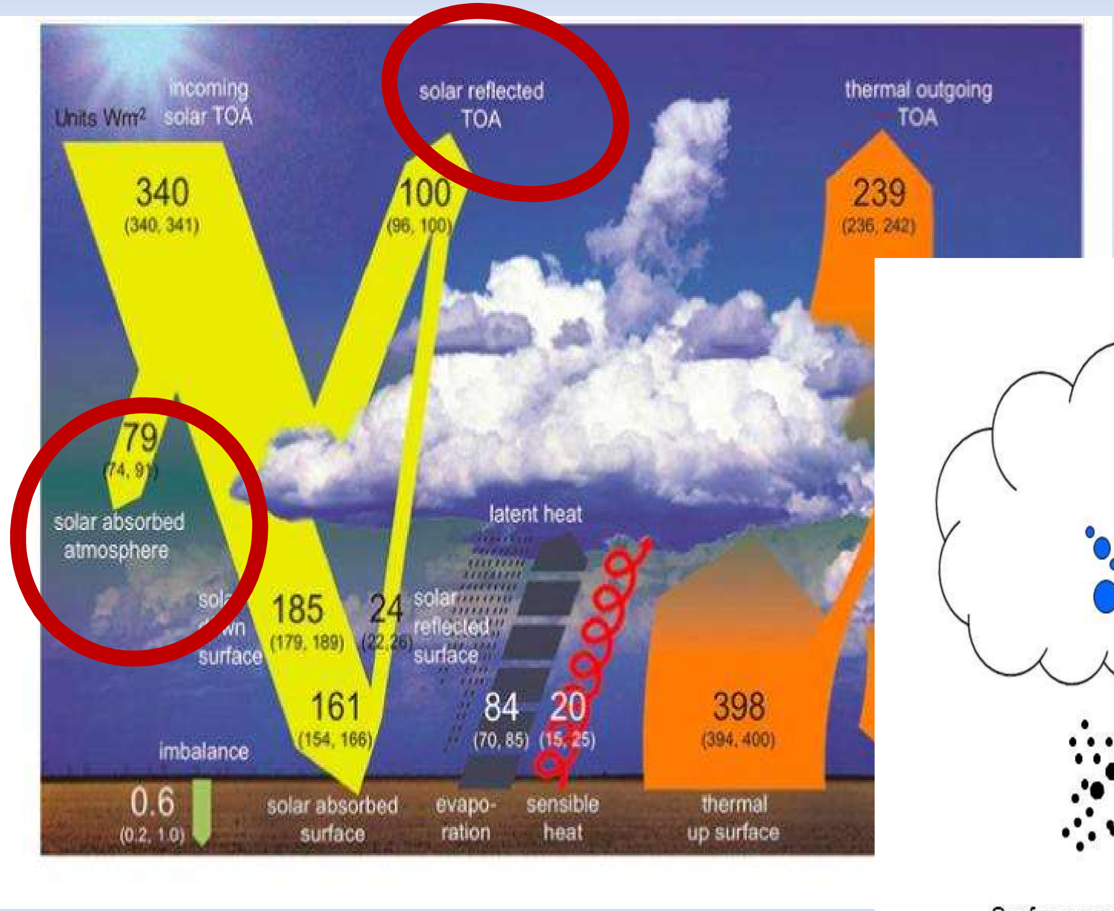
Overview

Aerosols and radiative forcing
Aerosol Optical Depth
Surface based AOD networks
Homogenization activities

PMOD/WRC as World Radiation Center

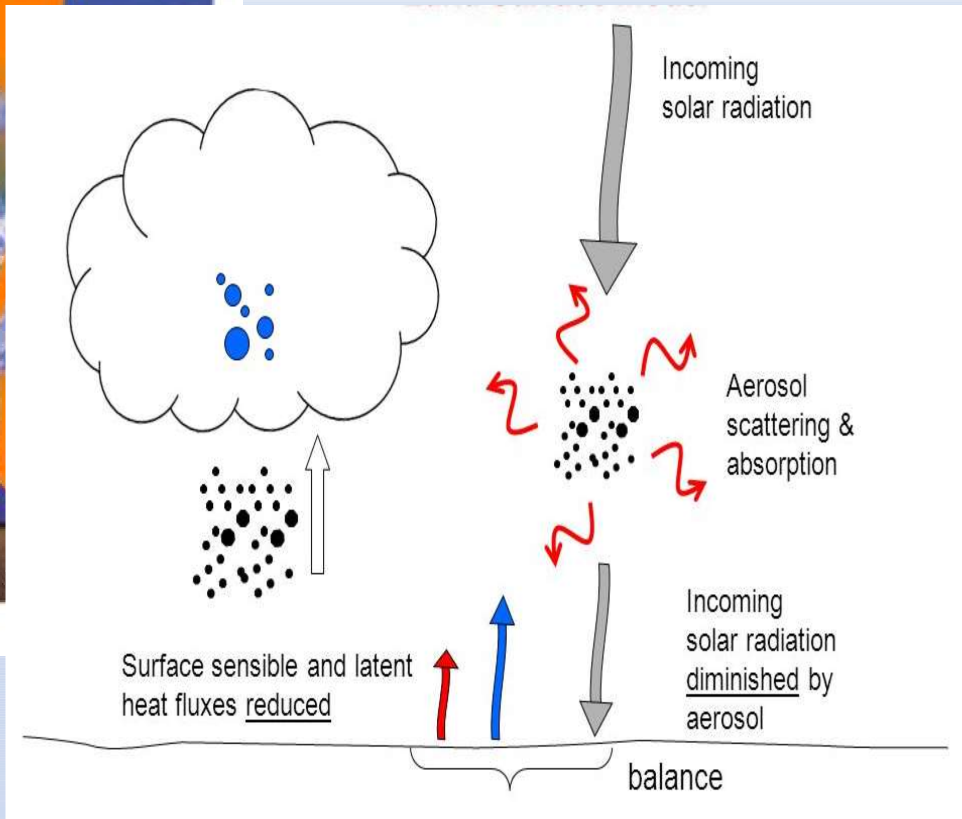


Aerosols and radiative forcing



Wild et al, 2013

Aerosols:
absorption scattering
Interaction with clouds

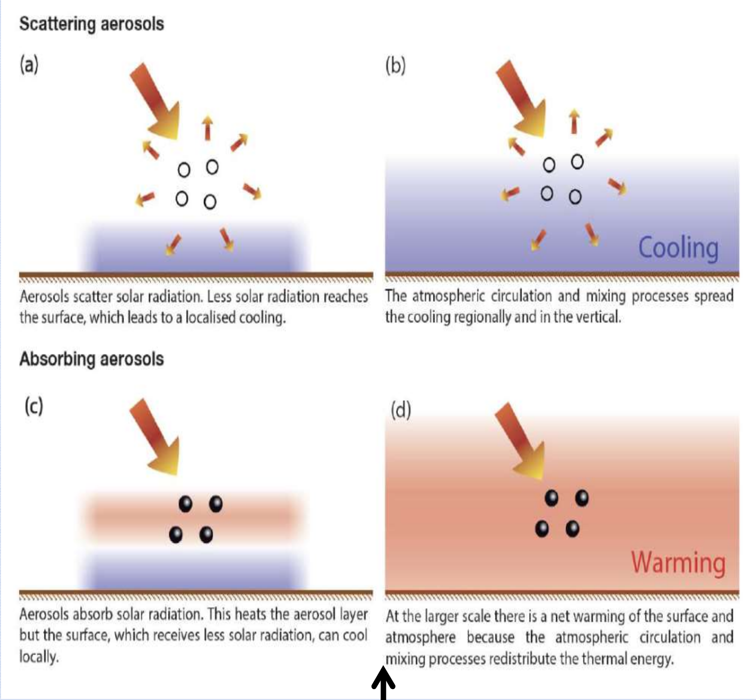


Aerosols and radiative forcing

Why are aerosols important?

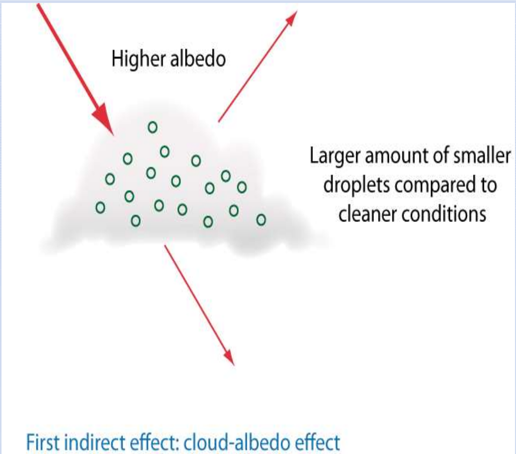
Because aerosols have much shorter lifetimes and more varied distributions than greenhouse gases, the net effect on global climate is hard to predict.

Aerosols can increase the reflectance of clouds.
They also may modify the lifetime of clouds by affecting precipitation.



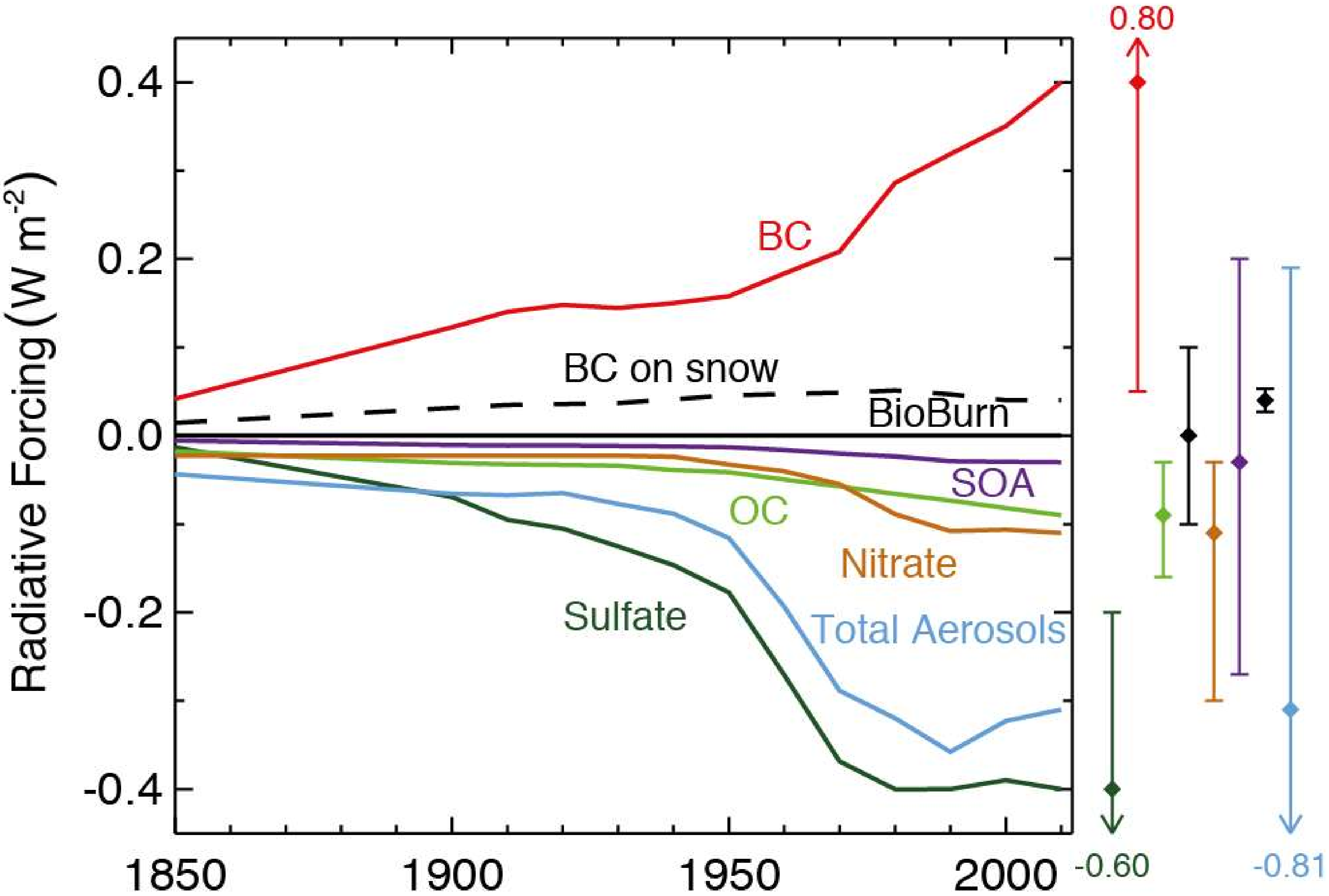
Aerosol Direct Effect

Aerosol Indirect Effect



***Source**: IPCC, Fifth Assessment Report, 2013*

Aerosols and radiative forcing

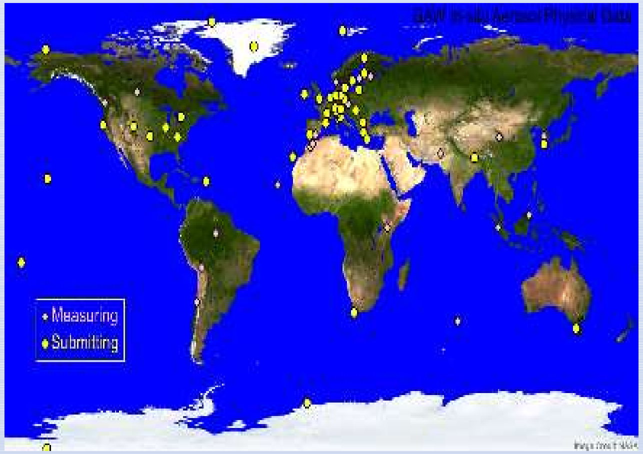


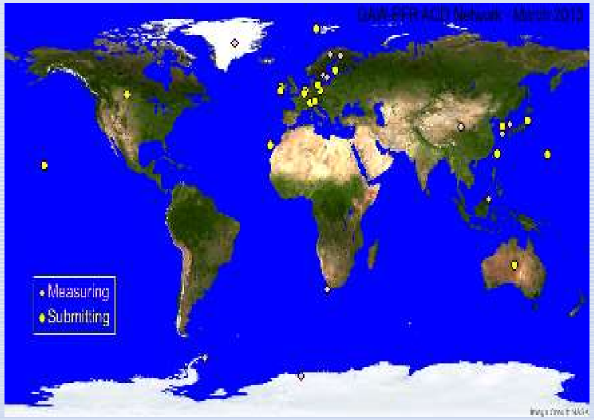
Aerosols and radiative forcing

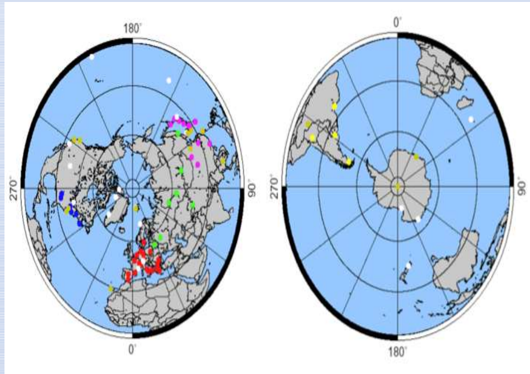
IN-SITU

AEROSOL OPTICAL DEPTH

LIDAR







Surface level
Health effects

Columnar
Radiative forcing

Columnar profiles

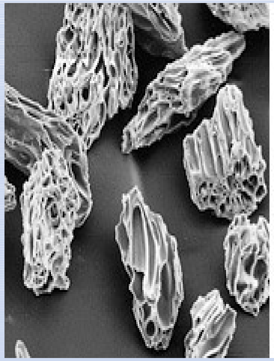
Aerosols ?

Suspended particles in the atmosphere

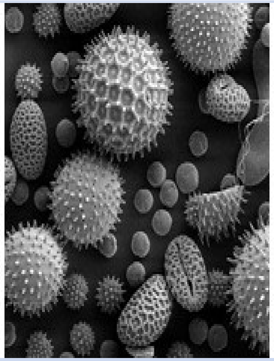
Ranging in size from a few molecules to tens of micrometers

Our main interest is aerosols with $0.1<r<20$ µm

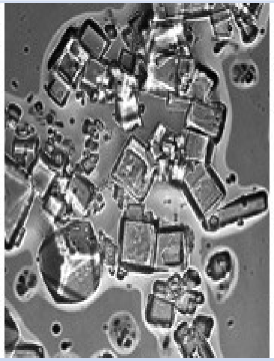
1 µm is an approximate separation between “fine” and “coarse” aerosols



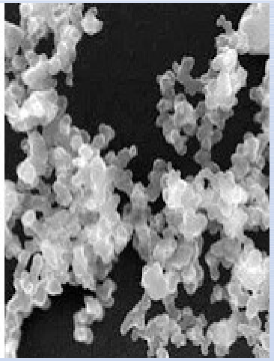
volcanic ash



pollen



sea salt



soot.

Optical Properties

Optical properties are important for several reasons

- Their effect on the radiative balance of the Earth's environment
- Their effect on heating of the atmospheric column which can change circulation and affect the water cycle
- Effect on visibility

What columnar aerosol properties are retrieved / used for studying their radiative effects ?

Aerosol Optical Depth (AOD) ~ aerosol amount

These optical measurements of light extinction are used to represent aerosol amount in the entire column of the atmosphere.

AOD is a unitless value and wavelength dependent.

Sample AOD values (visible):
0.02 - very clean isolated areas.
0.2 – fairly clean urban area
0.4 – somewhat polluted urban area
0.6 – fairly polluted area
1.5 – heavy biomass burning or dust event

What is Aerosol Optical Depth?

"AOD is a quantitative measure of the extinction of solar radiation by the integrated columnar aerosol load"

"AOD is the single most comprehensive variable to remotely assess the aerosol burden in the atmosphere"

"AOD is a key variable in climate modelling, aerosol closure experiments and satellite verifications"

Aerosol Optical depth

Optical Depth *is not* Optical Thickness

Definitions in AMS Glossary of Meteorology

(consistent with WMO CIMO Guide or GAW#162 Report)

optical thickness : The dimensionless line integral of extinction coefficient along any path in a scattering and absorbing medium.

optical depth: The optical thickness measured vertically above some given altitude.

Turbidity and Visibility

Turbidity (AOD) optical extinction along vertical path

Ångström turbidity ≈AOD@1μm **AOD = b *$\lambda^{-\alpha}$**

Volz, Schüepp turbidity ≈AOD@500nm

Visibility (meteorological range) along horizontal path

$V = 1/\tau \ln(1/\varepsilon) = 1/\delta * 3.912$ (Koschmieder formula)

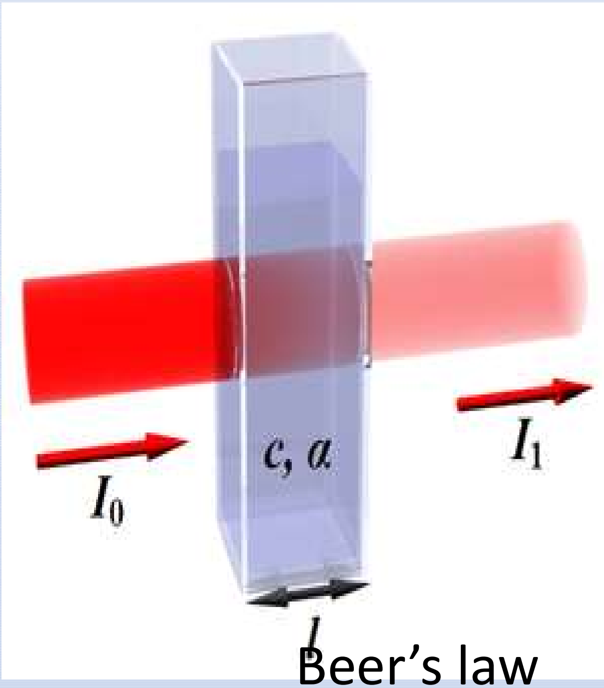
	Å(β)	AOD (500nm)	V(km)
Clean	0.02	0.05	80
Clear	0.1	0.25	16
Hazy	0.2	0.5	8
Turbid	0.4	1.0	4

Extinction of Sunlight

- **Absorption** in specific spectral domains by molecular (H_2O, CO_2, O_3, …) and particulate matter (aerosols) Radiative energy is deposited in the atmosphere in form of heat or chemical reactions.
- **Scattering** by particles of a wide range in size from molecules to cloud droplets.
  Scattering is a continuous process, redistributing radiation in all directions for all wavelengths, but does not transfer energy.
- **Extinction** = Absorption + Scattering

What columnar aerosol properties are retrieved / used for studying their radiative effects ?

Aerosol Optical Depth (AOD) ~ aerosol amount



Beer's law

$$I = Io * e^{-m\tau}$$

I = measurement
Io= TOA / calibration
τ = total extinction

$$T_{(wl)} = \tau_{o3} + \tau_{aer} + \tau_{Ray} + \tau_{cl} + \tau_{gas}$$

Aerosol Optical Depth

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

where *I* is the measured irradiance (in arbitrary units), I_0 the calibration constant, ε the diffuse light scattered into field-of-view, *r* the Sun-Earth distance (in astronomical units), m_x are the respective air masses for molecular scattering, ozone absorption and aerosol extinction with corresponding optical depth δ_x, ϑ is the apparent solar zenith angle, *p* is the actual and p_0 the standard atmospheric pressure.

$$\delta_A(\lambda) = \frac{\log\left(\frac{I_0(\lambda)}{I * r^2}\right) - \frac{p}{p_0} m_R(\theta)\delta_R(\lambda) - m_{O3}(\theta)\delta_{O3}(\lambda)}{m_A(\theta)}$$

Air mass approximations

Definition: (relative) Air mass is the density integral of an extinction component along a slant path through the atmosphere related to its vertical integral which defines unit air mass.

For a plane-parallel and homogeneous atmosphere all air masses would be equal to $m=1/\cos(sza)$, but for a curved and refracting atmosphere a numerical integration must be performed for each solar zenith angle *sza* using a realistic atmospheric model of vertical density and refractive index distribution.

Tabulated results of such calculations were published by several authors together with fitted approximation formulas such as those given below:

Rayleigh air mass $$m_R = \frac{1}{\sin(e) + 0.50572(e + 6.07995)^{-1.6364}}$$ (Kasten, 1989)

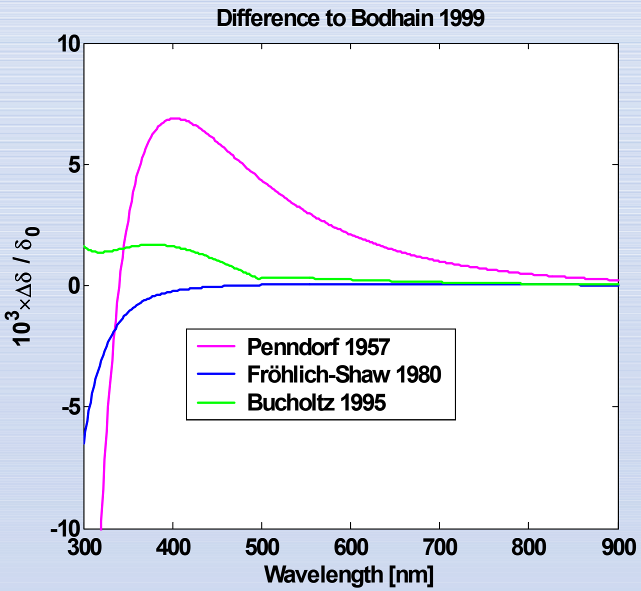
Ozone air mass $$m_{O3} = \frac{R + h}{\sqrt{(R + h)^2 - (R + r)^2 \times \cos^2(e)}}$$ (Komhyr, 1980)

Aerosol air mass $$m_a \approx m_{H2O} = \frac{1}{\sin(e) + 0.0548 \times (e + 2.65)^{-1.452}}$$ (Kasten, 1966)

Where *e* is the apparent solar elevation angle, *R*=6370km the mean Earth radius, *r* the station height above sea level in km and *h* the height (≈22km) of the ozone layer. The aerosol air mass is further approximated by water vapour air mass, which has similar scale height.

Rayleigh optical depth

- Rayleigh optical depth δ_R is proportional to atmospheric pressure
- Refractive index of air is wavelength dependent
- King depolarisation factor depending on air composition (CO_2)
- Explicit integrations fitted in wavelength by several authors



Approximation by Fröhlich & Shaw

$$\delta_R(\lambda) = 0.00864 \times \lambda^{-(3.916 + 0.074\lambda + \frac{0.050}{\lambda})} \times \frac{p}{1013.5}$$

[wavelength λ in μm]

Extraterrestrial Calibration I_0

I_0 can be determined from:

A. Extrapolation through the atmosphere: Langley methods.
B. Comparison to reference instrument
C. Laboratory calibration combined with solar spectrum.

Calibration and AOD errors

$$\delta(\lambda) = \frac{1}{m}\left[\ln(I_0) - \ln(I) - 2\ln(r)\right]$$

$$\frac{1}{m}\left[\ln\left(I_0 \times \left(1 + \frac{\Delta I_0}{I_0}\right)\right) - \ln(I)\right] = \delta + \frac{1}{m}\ln\left(1 + \frac{\Delta I_0}{I_0}\right) = \delta + \Delta\delta$$

Calibration error

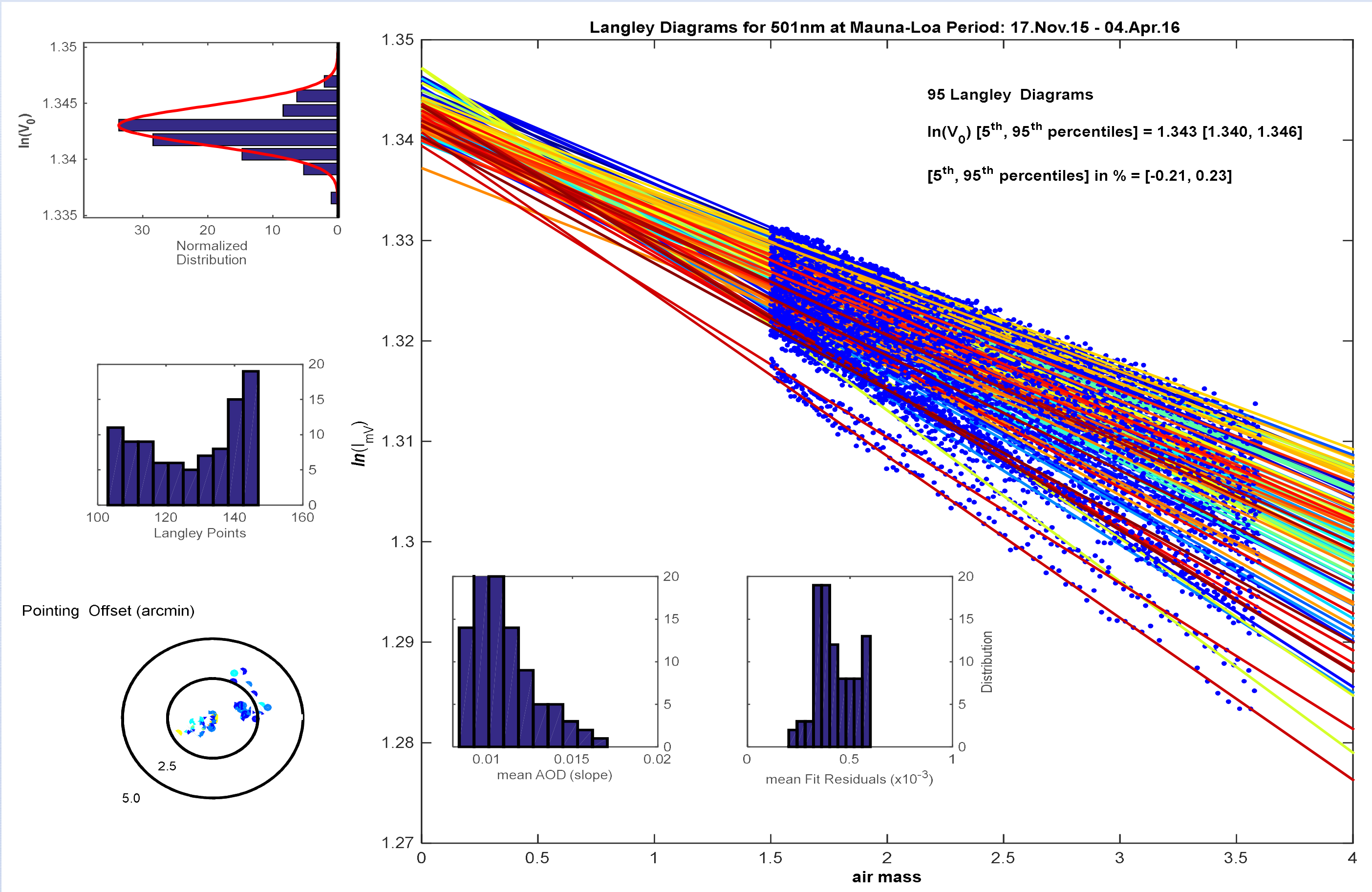
AOD error

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

$$WMO\text{–}GAW: \Delta\delta = 0.005 + \frac{0.01}{m}$$

An uncertainty of Calibration of 1% is required in GAW

Langley calibration



Langley plots for Mauna Loa observatory from November 2015 to April 2016.

Measurement Techniques

- **Pointed spectral radiometers (Sunphotometers)**

Solar irradiance in narrow field-of-view
Calibration of extra-terrestrial irradiance
Requires two-axis sun tracker
Atmospheric transmission

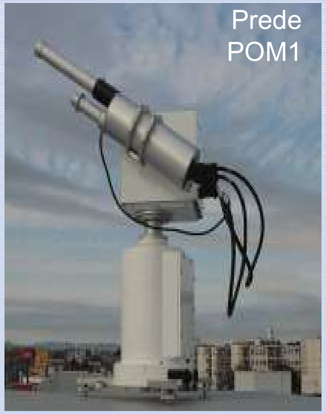
- **Shaded hemispherical radiometers**

Solar global and diffuse hemispherical irradiance
Calibration of extra-terrestrial value and cosine response
Rotating shadow band
Atmospheric transmission

- **Sun and Sky-scanning radiometers**

Solar irradiance and Sky radiance in narrow field-of-view
Calibration of extraterrestrial value and absolute radiance
Requires two-axis pointing robot
Atmospheric transmission, scattering phase function

Instrument pictures



Specifications for Sun photometers

- Handheld instruments are inadequate for contemporary needs.
- Sampling rate: 1 observation/minute
- Timing accuracy <10 second, time reporting in UTC
- Site coordinates accuracy of 15arcsec
- Measurements resolution 1/5000 of full scale or better
- Full Field_of_View 2.5°, slope angles 1°; tracking <0.25°
- Primary channels

Primary channels	368±2/<6nm	412±2/<6nm
(center/bandwidth)	500±3/<11nm	862±4/<11nm
(additional channels)	778±2/5; 675±3/11; 610±2/11nm	

- Ancillary data for air pressure, temperature and humidity
- Daily ozone total column at station or at nearby Dobson site
- Raw measurements should be archived with results

According to WMO CIMO Guide (1996), BSRN (2000) and GAW specifications.

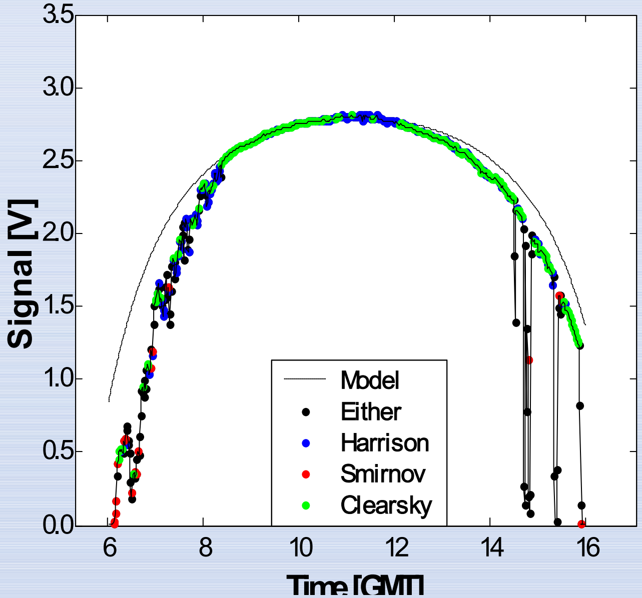
Available Instruments

Commercially available spectral Radiometers for Aerosol measurements						
Model	**Manufact.**	**Channels**	**Viewangle**	**Network**	**Remarks**	**Software**
Pointed Sunphotometers						
SP02 (-L)	Carter-Scott	4: 412, 500, 675, 862	5° (2.5°)			
PFR	PMOD	4: 368, 412, 500,862	2.5°	GAW-PFR	incl. DAQS	
PSR	PMOD	Spectral	2.5°		incl. DAQS	
SPUV-6 (10)	YES	6: 368, 500, 615, 778, 870, 940	2.5°		incl. DAQS	optional
Rotating Shadowband Radiometer						
MFR-7	YES	6: 415, 500, 615, 673, 870, 940	2π / 3.5°		incl. DAQS	optional
Sky-Scanning Radiometers						
CE318-1	Cimel	5: 440, 670, 870, 936, 1020	1°	AERONET	Filterwheel, tracker incl.	basic incl.
POM-01L	Prede	7: 315, 400, 500, 675, 870, 940, 1020	1°	SKYNET	Filterwheel, requires PC	free UNIX SW
SP1A	Schulz	18 WMO +	1° imaging		Filterwheel, requires PC	included

List is not exhaustive, further instruments may be available from other companies

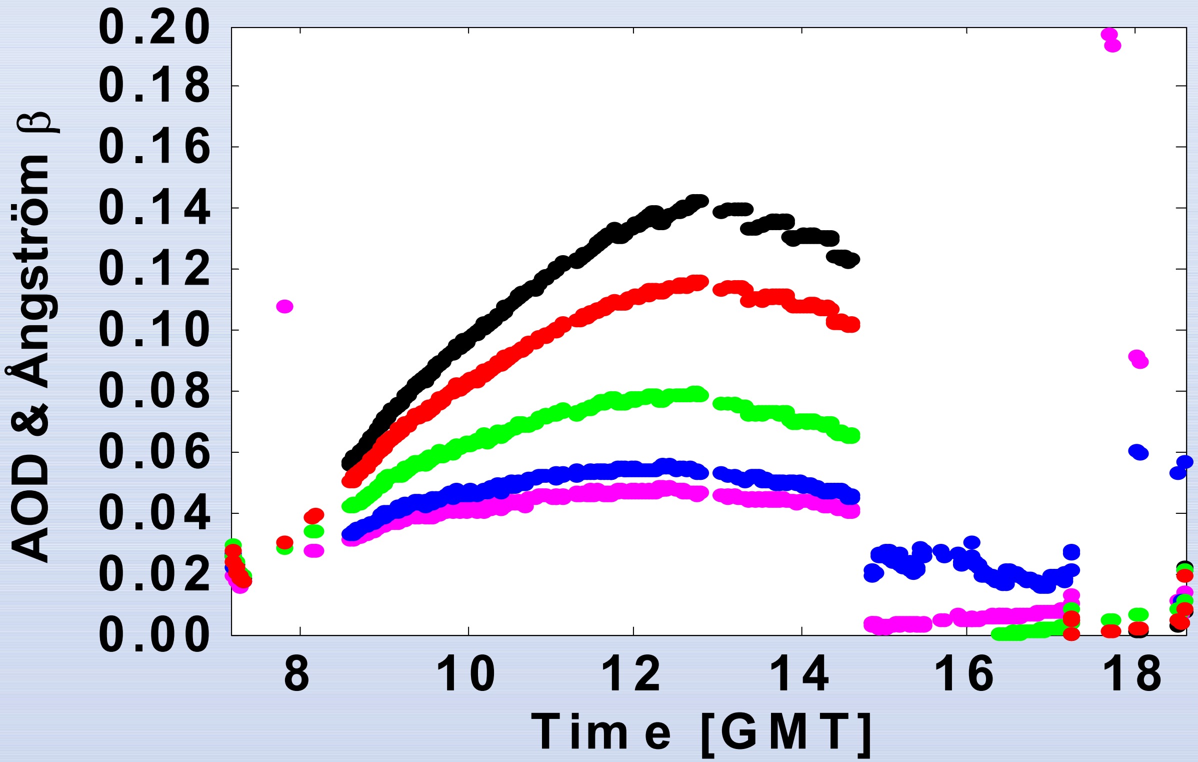
QC: Cloud Filtering

- Automated measurements need objective cloud filtering algorithm
- Thin cirrus clouds are hard to detect
- Harrison: $\Delta I / \Delta m < 0$ under clear sky works well while air mass changes quickly, most useful for Langley calibrations
- Smirnov: AOD varies more slowly than cloud perturbations based on rapid 'Triplet' measurements
- Additional smoothness filtering using second derivatives of signal or AOD.



Cloud filtering example with broken thin clouds in the morning, haze and thicker clouds in the afternoon.

QC: Cleaning

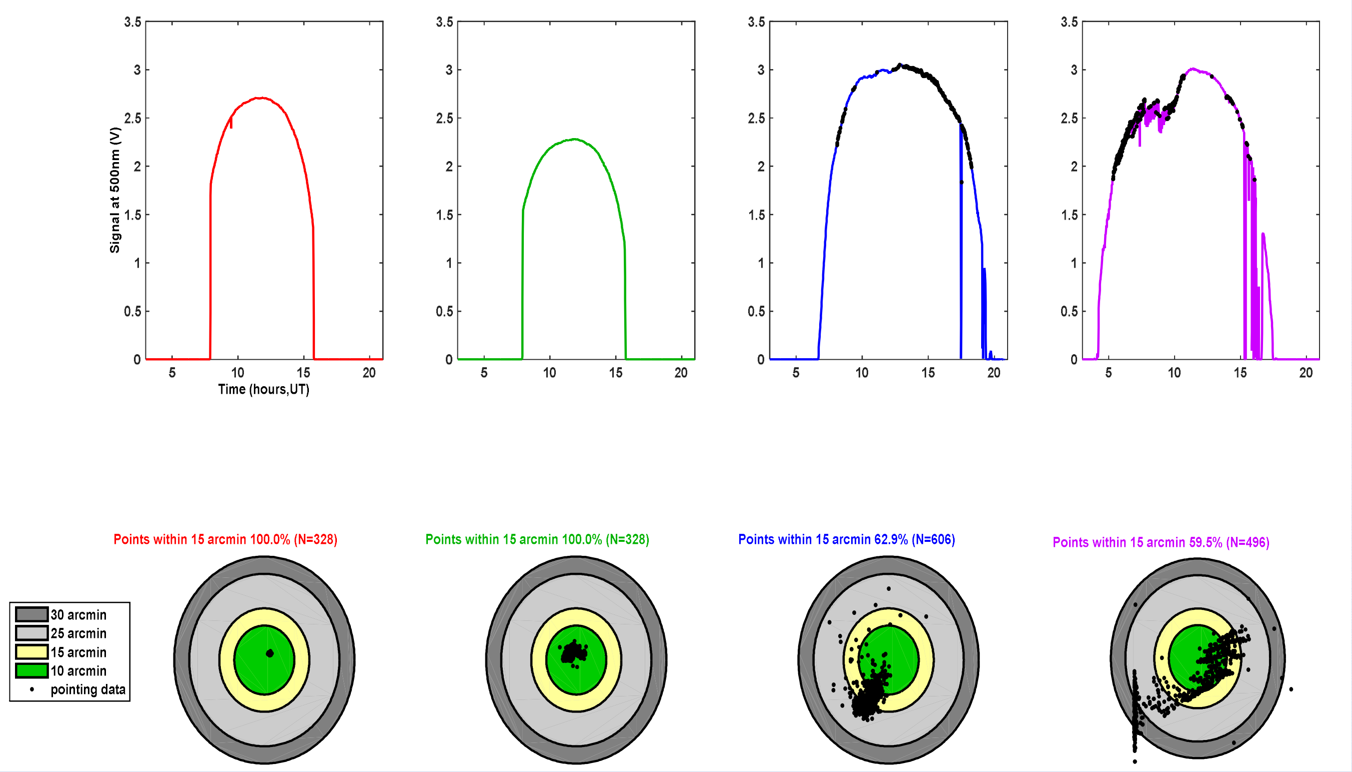


Neglected maintenance (cleaning) → erroneous results

Often hard to detect – always awkward to correct

Limited capability of automated tests → manual checks required

QC: Sun tracking

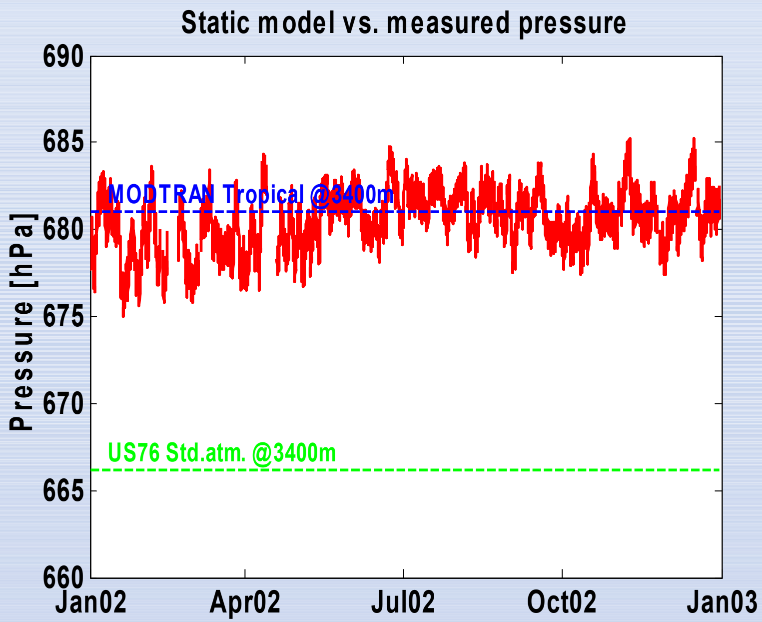


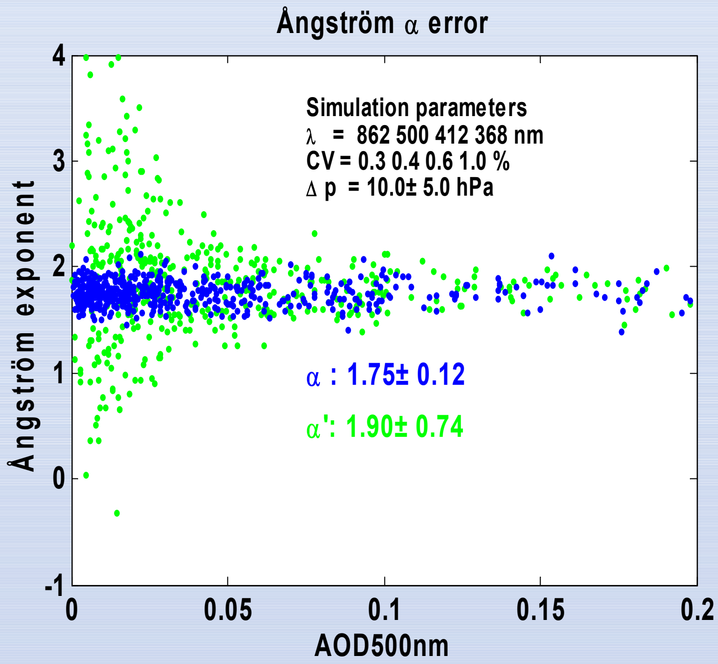
Sun tracker misalignment & hysteresis causing AOD artefacts

Individual checks and tight filtering required, possible with PFR!

QC: Atmospheric Pressure

- Rayleigh $\delta_R(\lambda,p)$ >> $\delta_A(\lambda)$ in UV-VIS range — U95(p) <±2hPa
- Davos station mean vs. sunny measurement: — $\Delta p \approx 3\pm6$hPa
- Differences among MODTRAN models (1km): — $\Delta p = 7$hPa





➢ small error in AOD <0.005 ⇒ larger error & scatter in α for small AOD

Reason: $\delta_R(862) \approx \delta_A(862)$, but $\delta_R(368)=0.35$, $\rho=4.0$; $\delta_A(368)=0.05$, $\alpha=1.5$

Instruments

Precision Filter Radiometer

PFR N21 at Riory, Japan

PFR specifications

- Automated, solar spectral radiometer
- 4 simultaneous channels at 862, 500, 412, 368nm using IAD interference filters
- Field of View: ±2.5° , slope angle 0.7°
- Dimensions: Ø90 x L300mm, Mass 3 kg
- Continuous, high cadence measurements
- Sensor at 20±0.1°C in range –25 ÷ 35°C;

  internal shutter; airtight N_2 flushed housing
- built-in pointing and barometric sensor
- Data logger with 30 day storage capacity

3 different cloud flags are determined for individual samples:

1. Harrison & Michalsky algorithm, modified for air masses <2
2. Triplet algorithm applied as moving filter on continuous samples
3. Optical thick (OD>3) clouds

GAW – PFR measurements

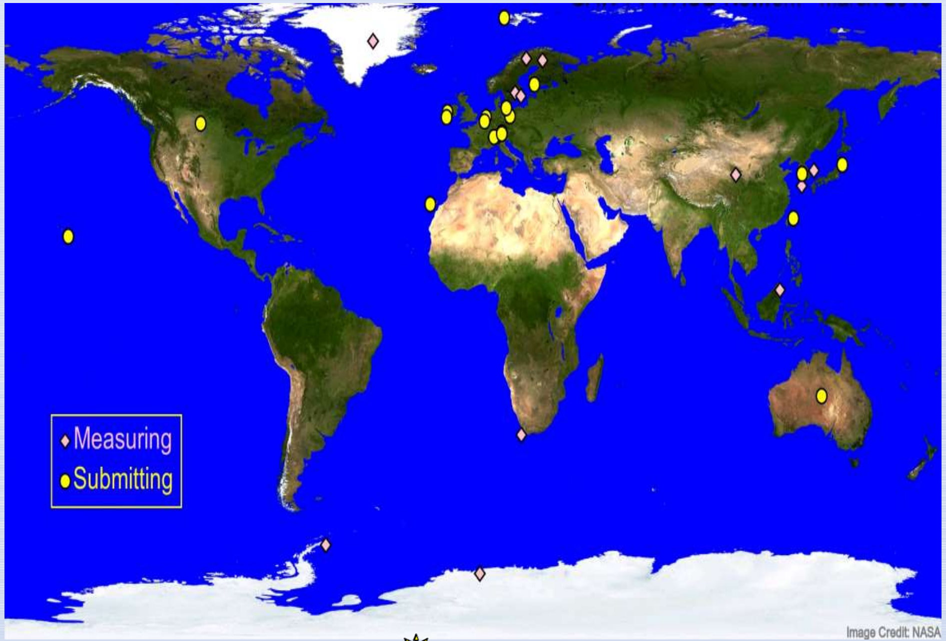
pmod wrc

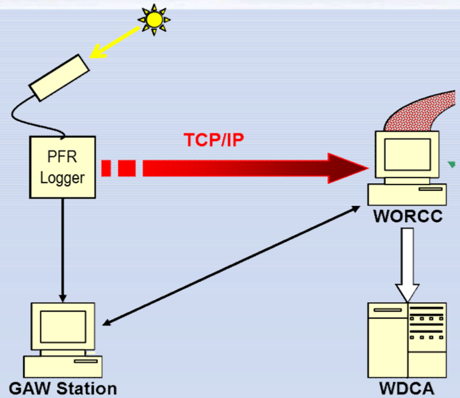
GAW-PFR Network

- Has uniform instrumentation and procedures for AOD measurement

12 global stations (PMOD)

17 associate stations (PFRs)





Users

Real time sub. To WDCA: 22

Europe
Davos, CH
Hohenpeissenberg, DE
Tenerife, ES
Mace Head, IR
Ny Alesund, NO
Jungfraujoch, CH
Sodankylä, FI
Summit, Gr
Jokioinen, FI
Kiruna, SE
Norrköping, SE
Visby, SE
Valentia, IR
Cabauw, NL
Zingst, DE
Lindenberg, DE
Zugspitze, DE

Asia
Danum Valley, (MA)
M. Walliguan (CN)
Anmyeon (SK)
Jeju Gosan (SK)
Ryori (JP)
Ulleungdo Dokdo (SK)

N. America
Mauna Loa, (US)
Bratts Lake (CA)

Australia
Alice Springs, (AU)

Africa
Cape Point (SA)

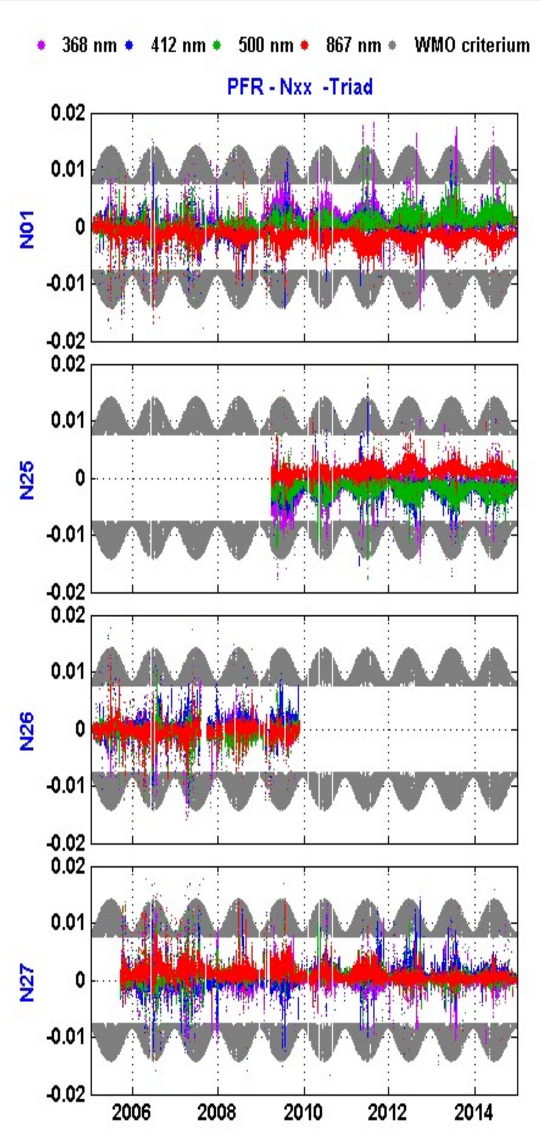
Antarctica
Marambio (FI)
Troll (NO)

PMOD WRC triad

pmod wrc

Long term stability

WORCC triad maintenance



The PFR reference triad has been operating near continuously since early 2005.

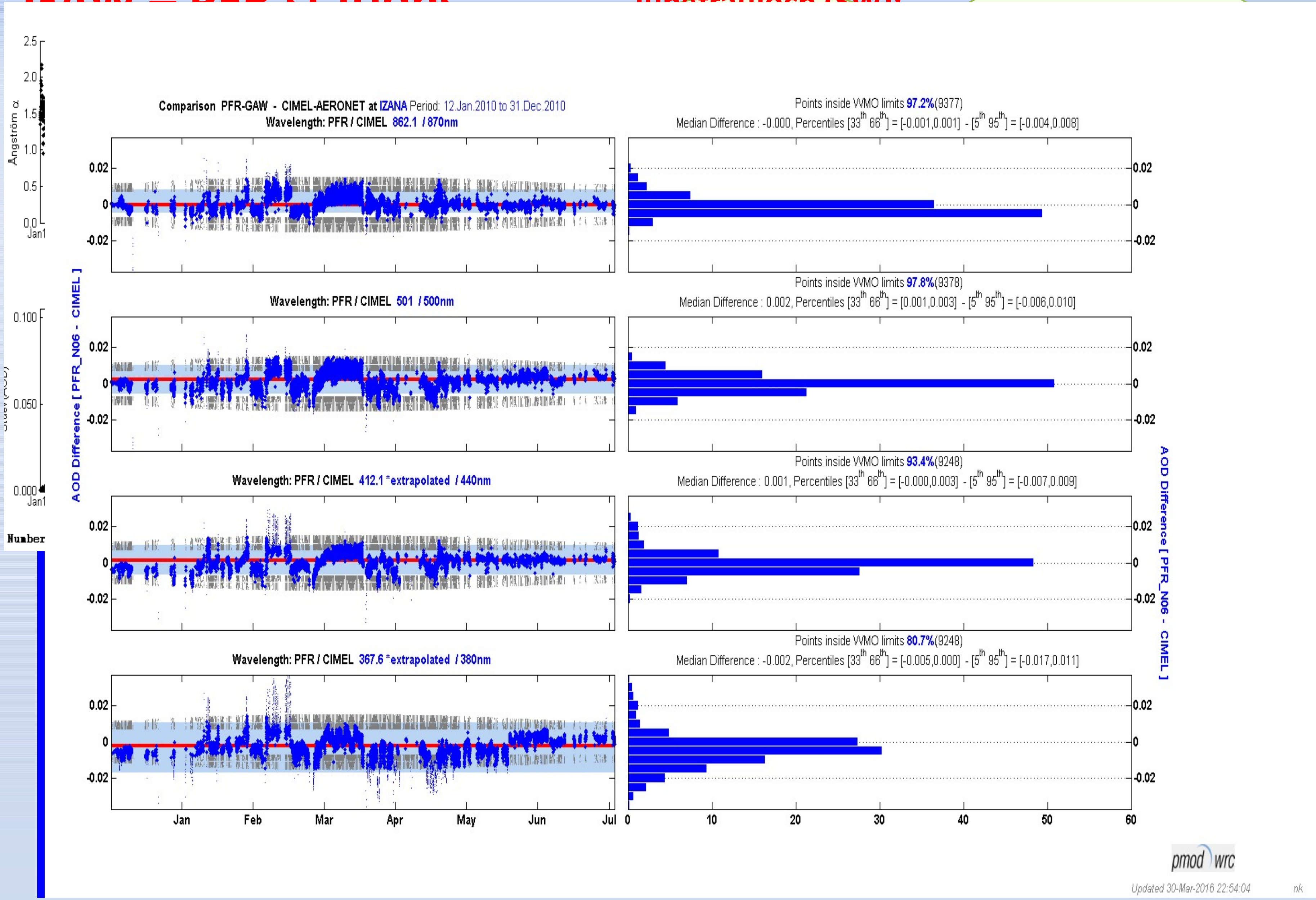
Interruptions were due to recalibrations by the Langley-plot technique at Mauna Loa, Hawaii or Izana, Canary Islands.

The scatter of aerosol optical depth measurements at 500 nm with the triad sunphotometers is less than
0.0002 ± 0.0011(1σ)
which is well within the WMO criterion of 0.005 + 0.01/m

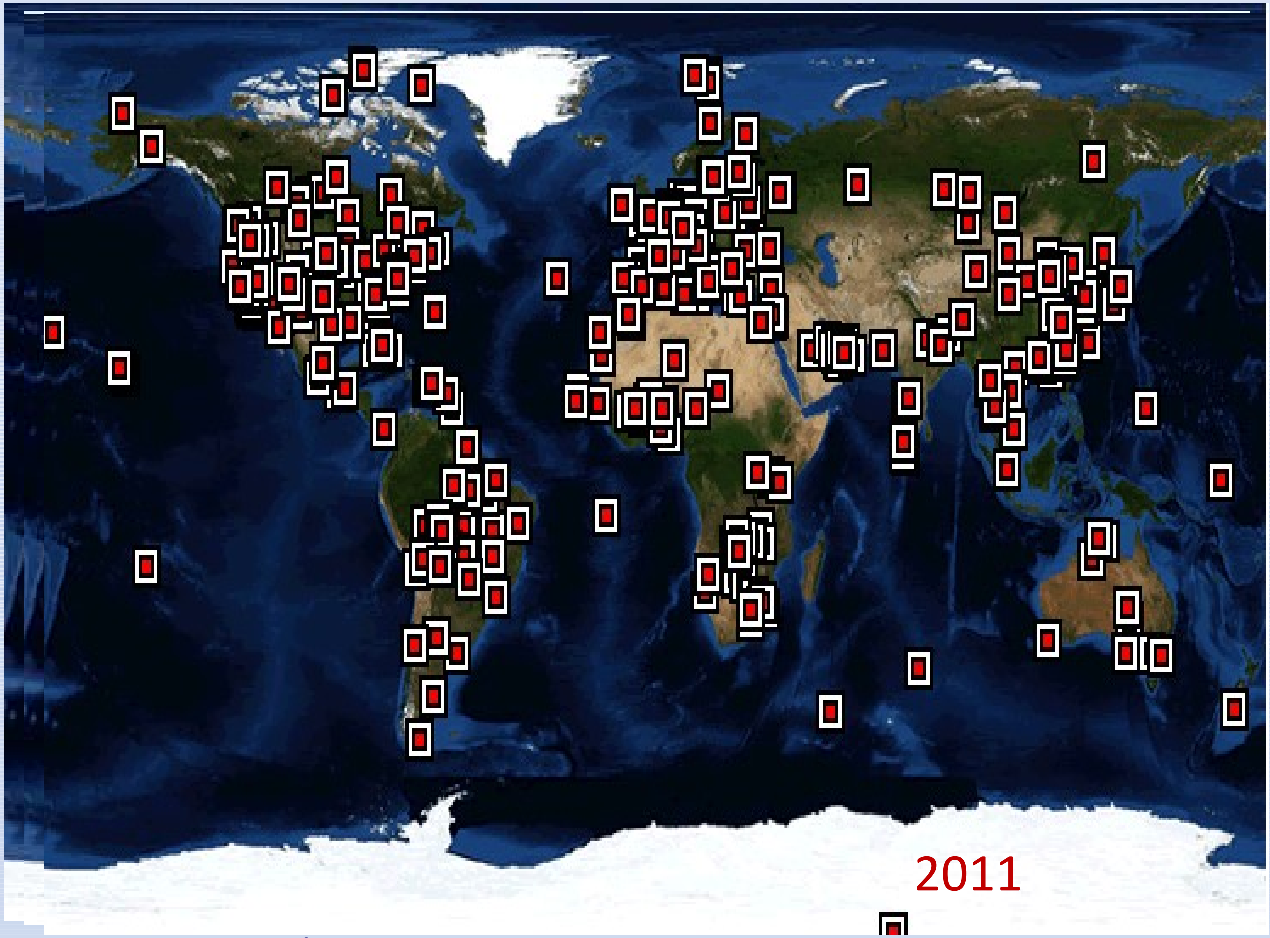
GAW – PFR stations

Jungfraujoch (SW):

Mt Walliguan



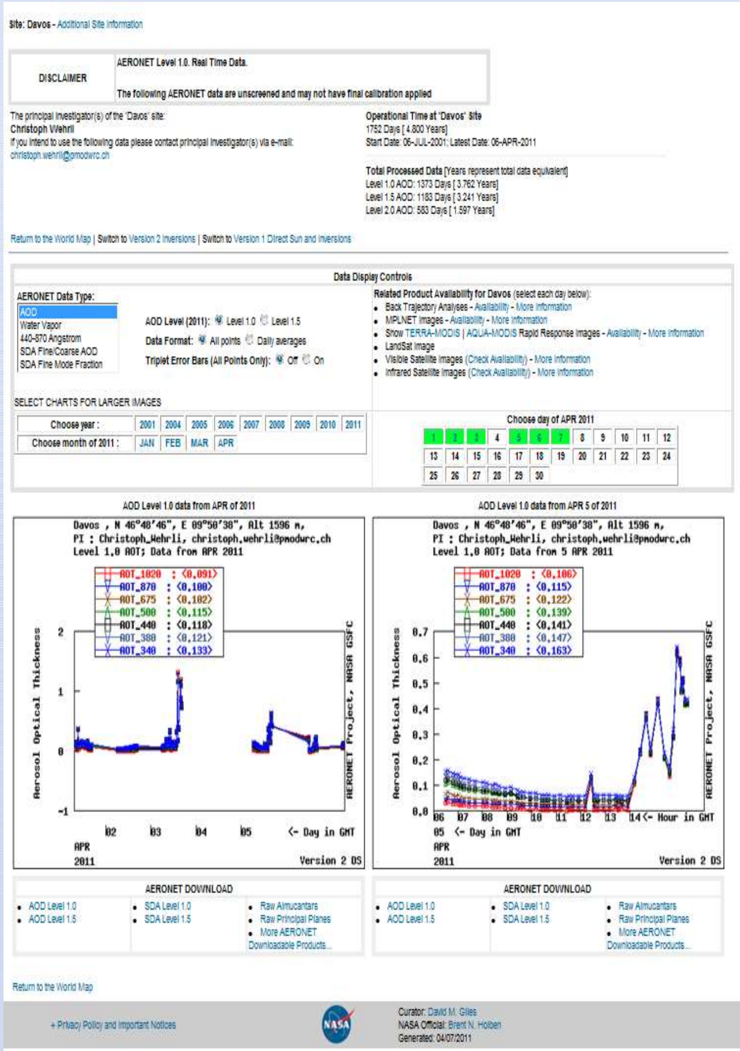
Aeronet Network



CIMEL Sun-photometer

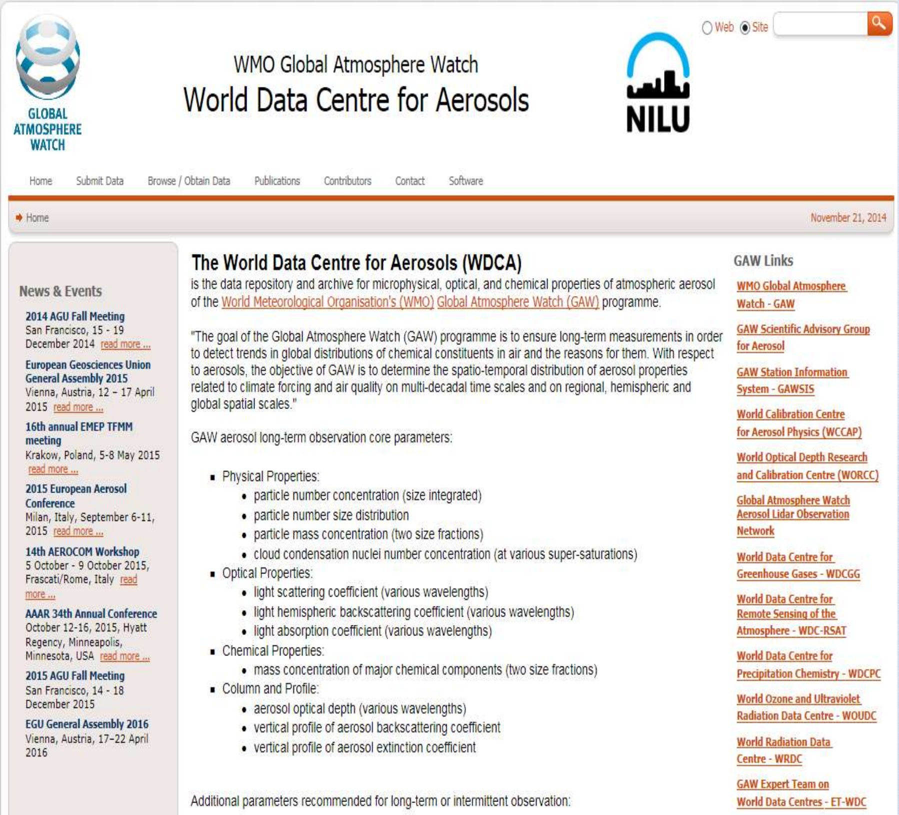
Open data access via website: http://aeronet.gsfc.nasa.gov/

Sunphotometer Networks



http://aeronet.gsfc.nasa.gov/

World Data Center for Aerosols

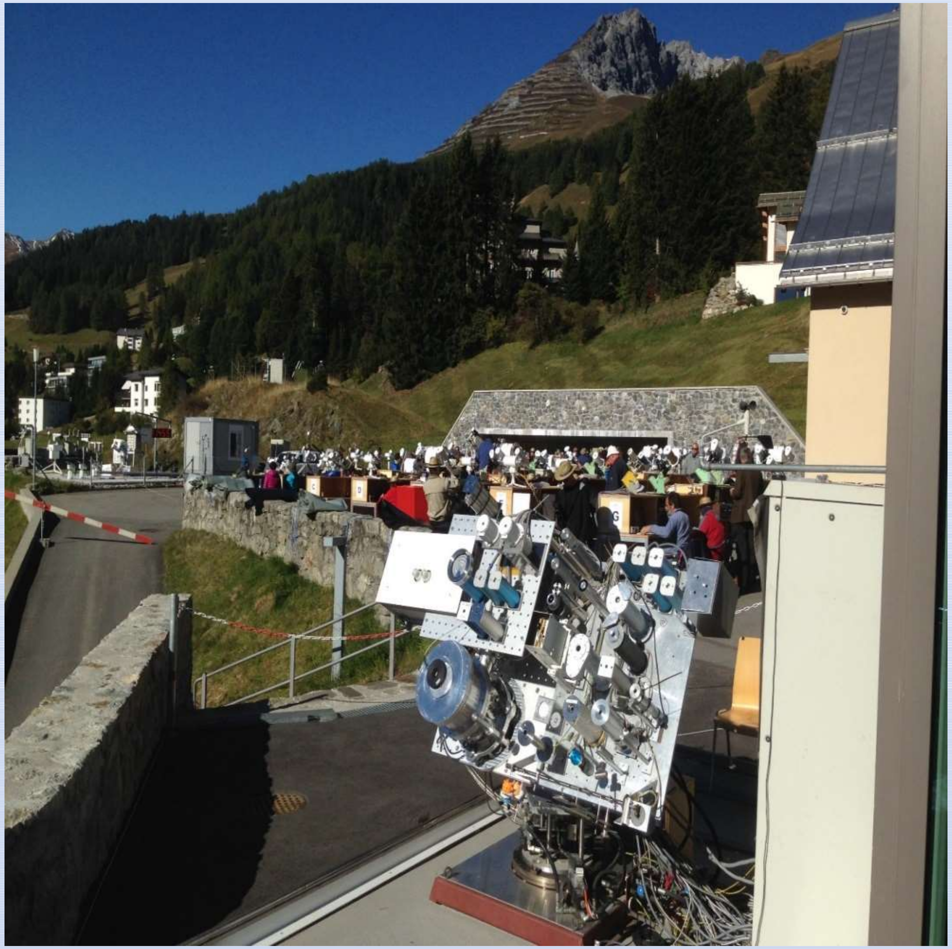


(IPC-XII) / 4th Filter-Radiometer Comparison (2015, Davos)

Sep, 28-Oct to 16, 2015, PMO Davos

- 12th International Pyrheliometer Comparison (IPC-XII)
- **4th Filter-Radiometer Comparison (FRC-IV)**
- 2nd International Pyrgeometer Comparison (IPgC-II).

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



http://projects.pmodwrc.ch/ipc-xii/

History ..

2000: FRC – I

Instrument signal comparison

7 wavelengths, 17 radiometers, 1 day measurements

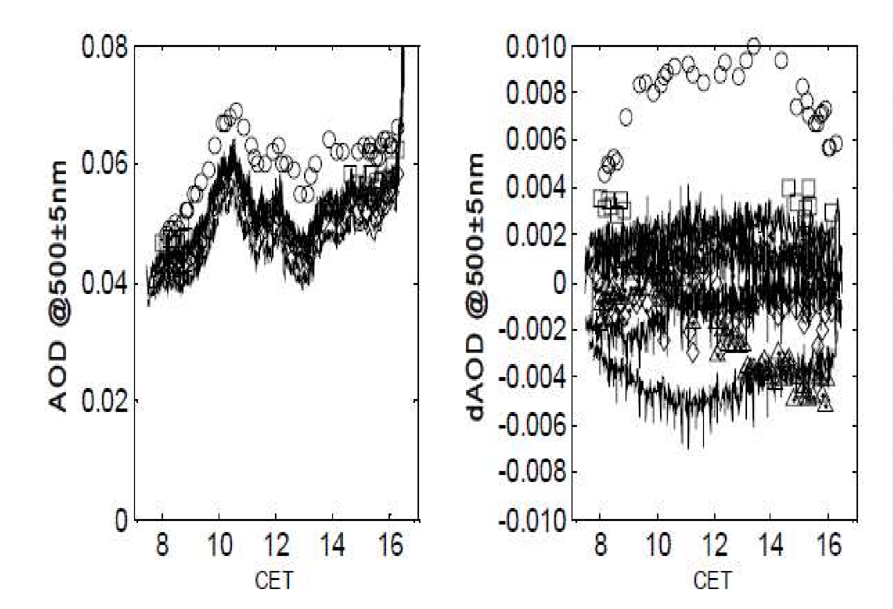
common processing → ∂δ≈0.016 @ 500nm (N=8)

2005: FRC – II AOD results

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

specific processing

comparison according to WMO recommendations (2004)

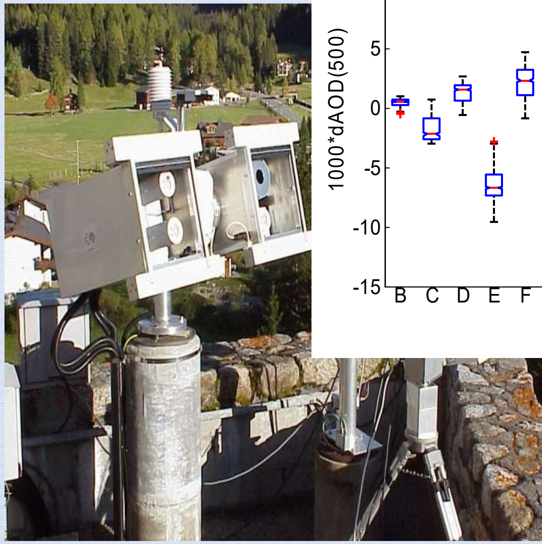


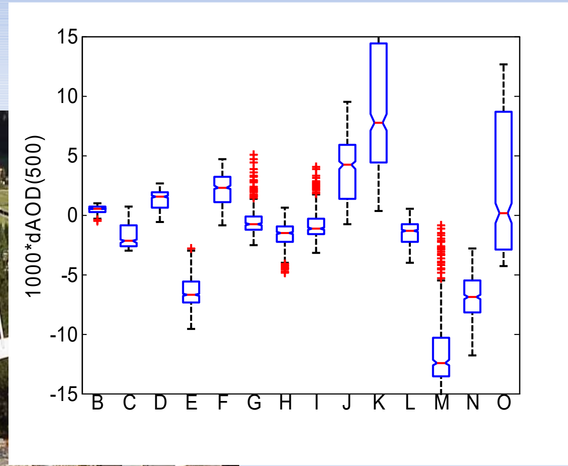
History ..

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

Assessment of AOD Quality

WMO Report No. 162 (2005) 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"

- 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:

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

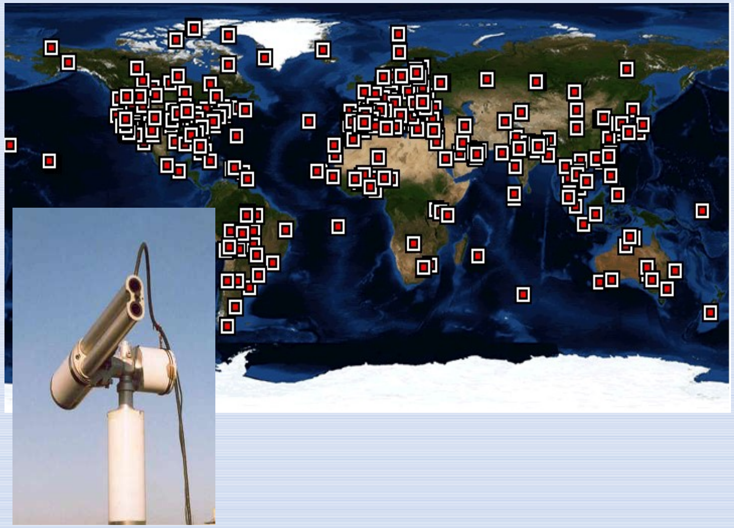
FRC/Participating Instruments

30 instruments – 15 groups – 12 countries

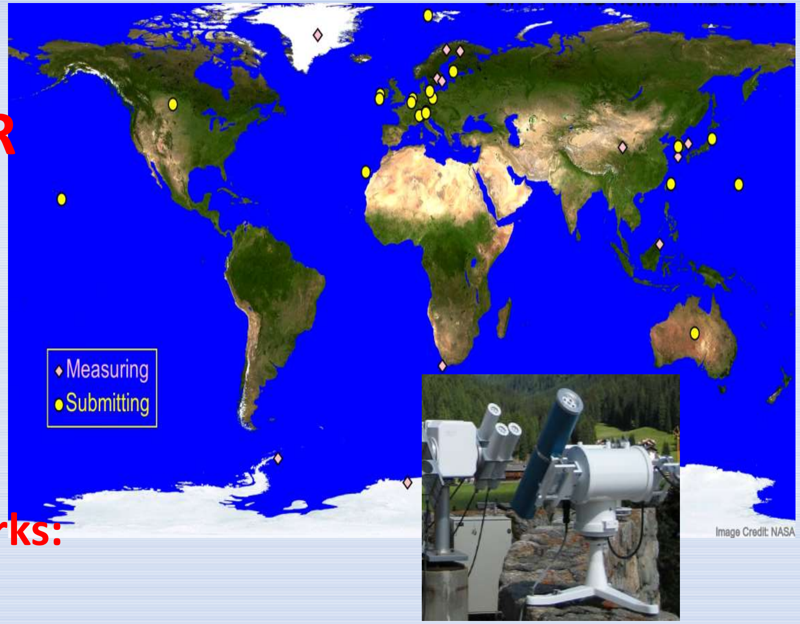
PFR	CIMEL	MFRSR	PSR	POM-2	SPO2	SSIM	Microtops
WORCC Triad-CH (3) SMHI-SE DWD-DE PMOD-CH (3) MeteoSwiss-CH	PMOD-CH AERONET-EU IZANA-ESP	DWD-DE NASA-US1 NOAA-US2 NOAA-US3	DWDa-DE DWDb-DE PMOD-CH	DWD-DE ARPA-IT JMA-JP KACARE-SA	BMa-AU NOAA-US	COFa-CA COFb-CA COFc-CA COFd-CA	MIC-GR
GAW-PFR	**AERONET-EU**	**SURFRAD**	**DWD**	**SKYNET**	**AU-NET**		
							
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, 1021 nm Fwhm: 10 nm FOV=1.2 deg Meas: ~15 minute	Global+diffuse wl: 415, 500, 610, 665, 860, 940 nm Fwhm: 10 nm FOV = variable Meas: 1 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 wl: 6 filters Fwhm: 5 nm FOV=2 deg Meas: 1 min	Direct sun spec wl: 6 filters Fwhm: 10 nm FOV=2.5 deg Meas: 1 min

Participating Instruments - Networks

AERONET

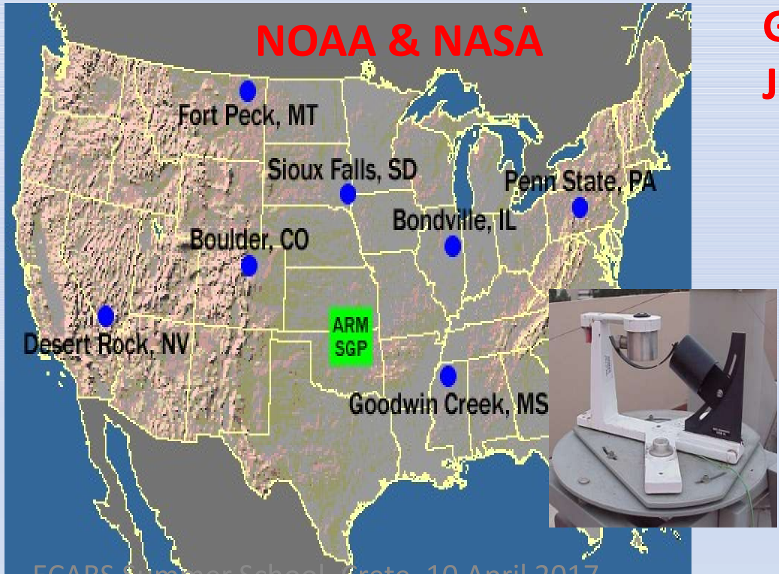


GAW-PFR

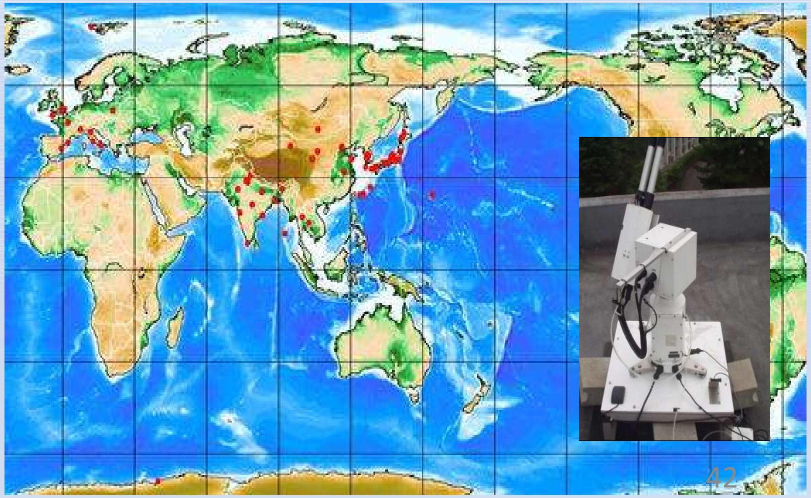


National Networks:
Australia
USA
Germany
Japan

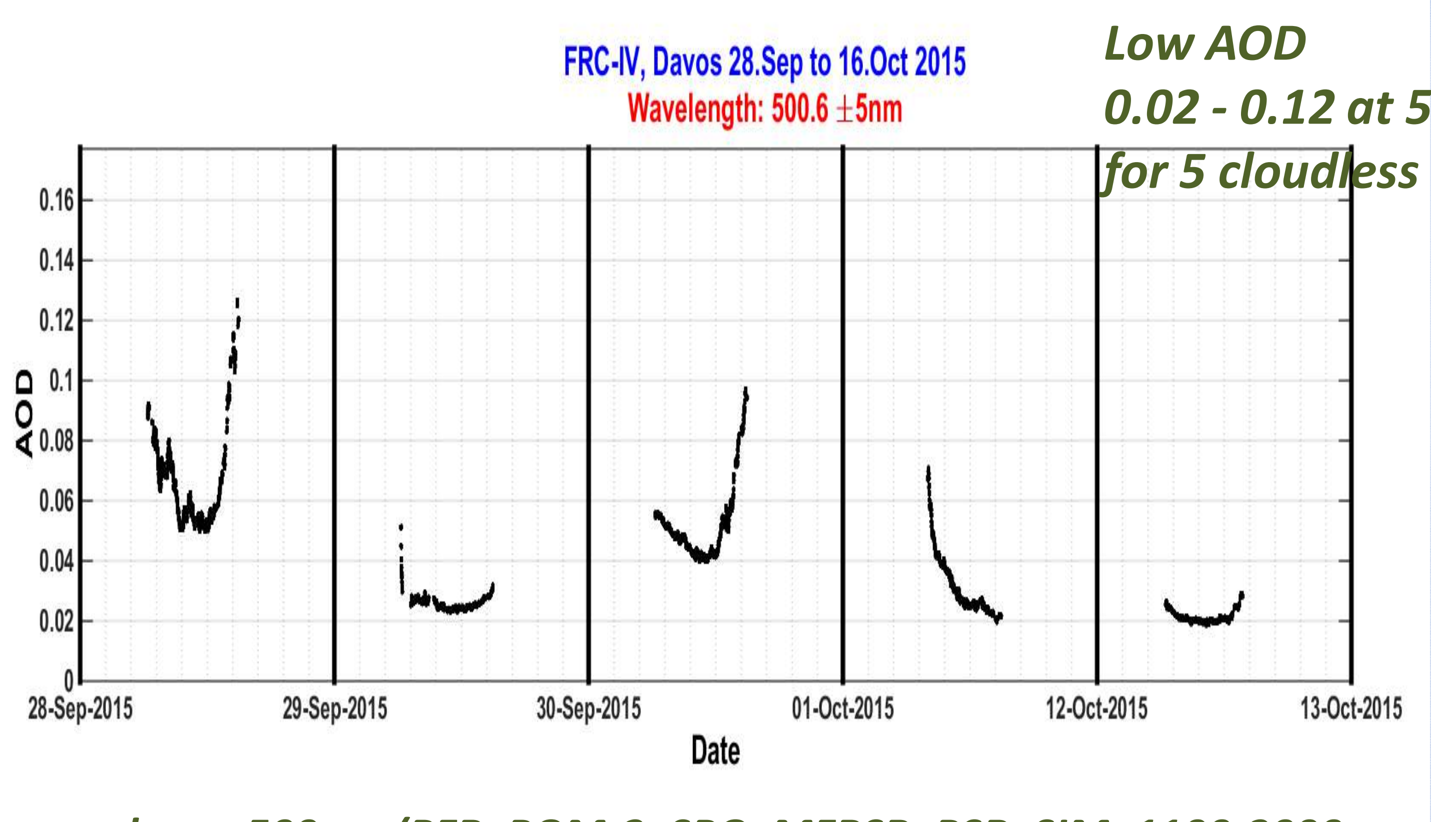
SURFRAD – MFRSR
NOAA & NASA



Skynet



AOD variability during the campaign



Low AOD
0.02 - 0.12 at 500nm
for 5 cloudless days

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

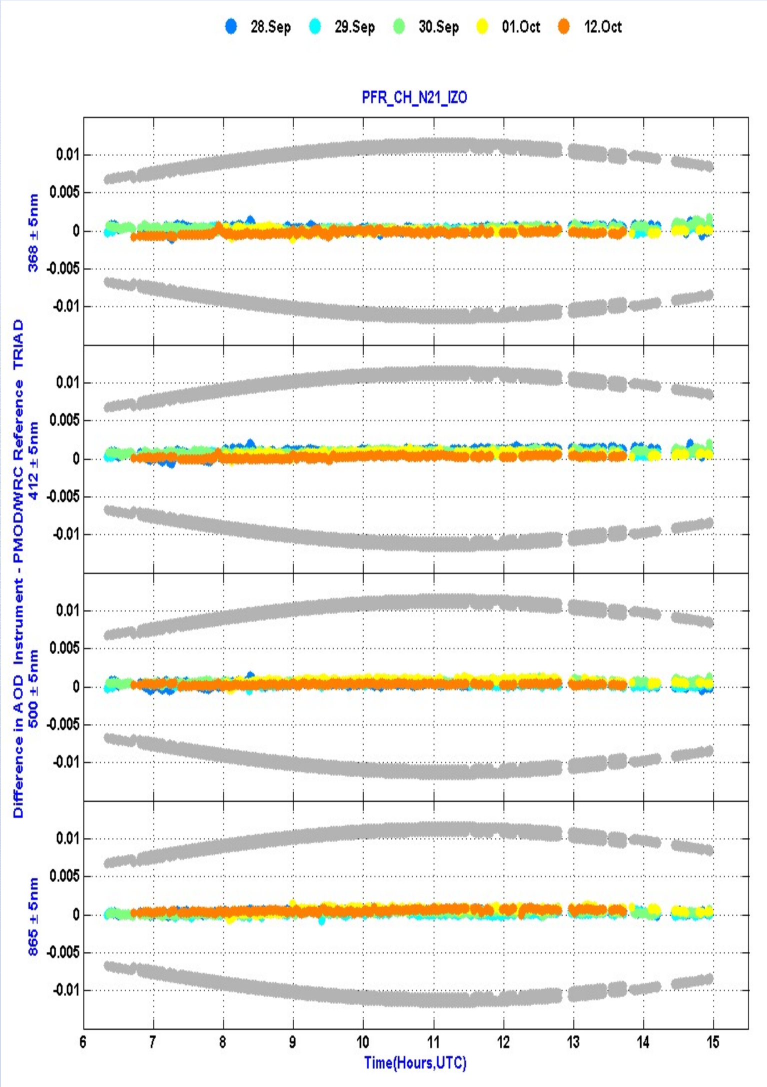
Duration ≥5 days OK

AOD500 within 0.040 ÷ 0.200 OD .. OK

U95: dAOD ≤ 0.005 + 0.01/m

Reference triad performance

WORCC triad



Izana, Tenerife, Spain

Mauna Loa, Hawaii, USA

N06, N21

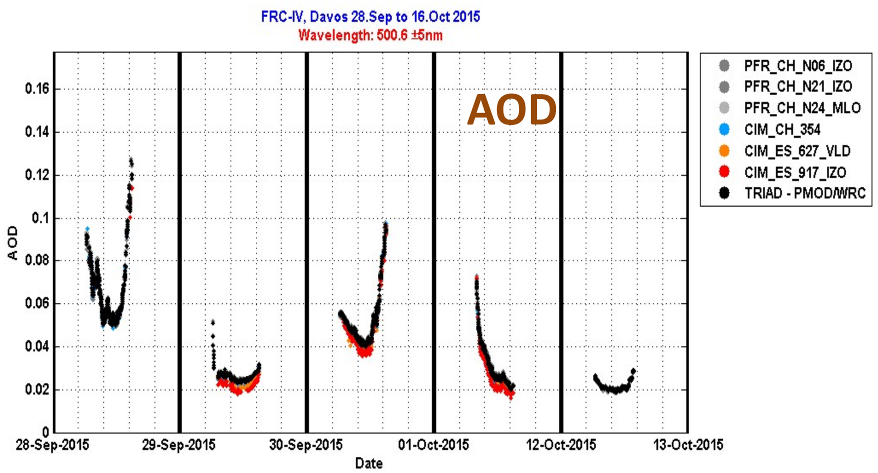
N24

Triad recalibration
Before the campaign

AOD dif <0.001

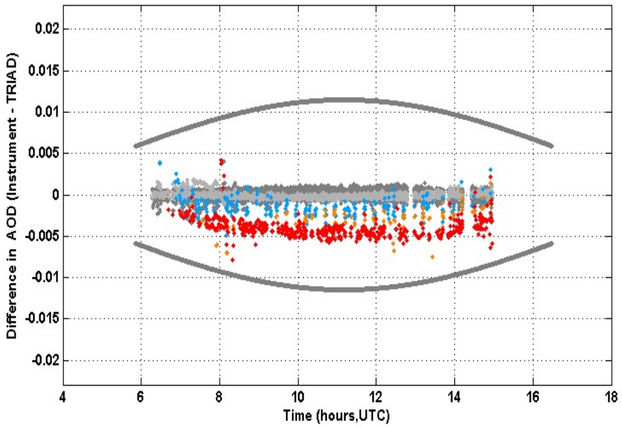
The 4th Filter Radiometer Comparison

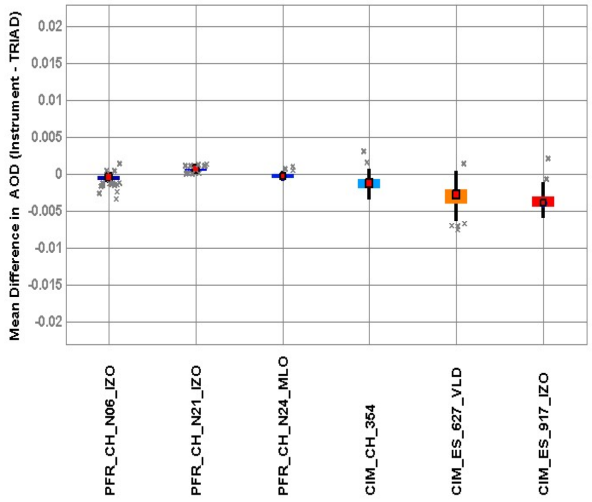
CIMEL (AERONET) instrument comparison at 500nm



98-99 % of data within WMO limits

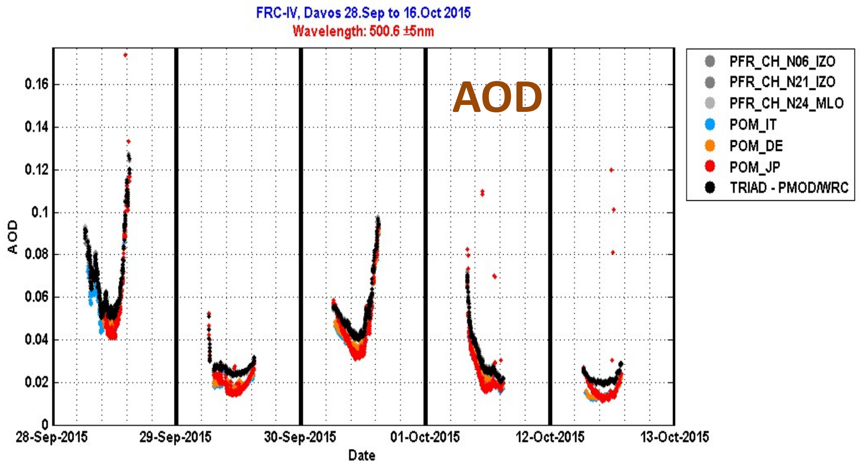
AOD differences





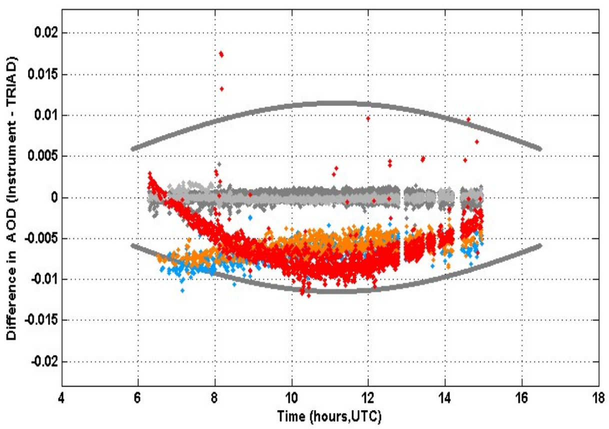
The 4th Filter Radiometer Comparison

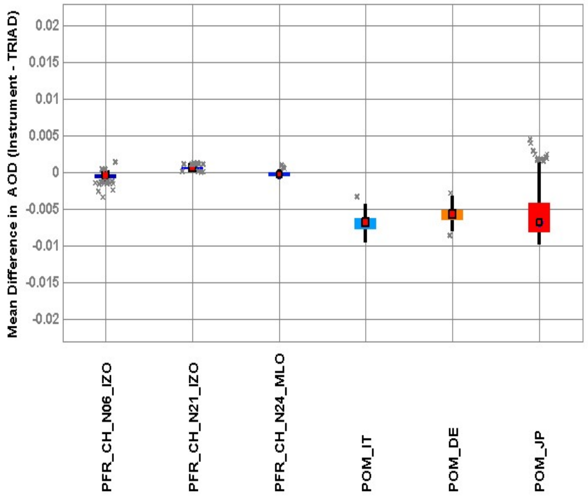
POM-2 (SKYNET) instrument comparison at 500nm



96-98 % of data within WMO limits

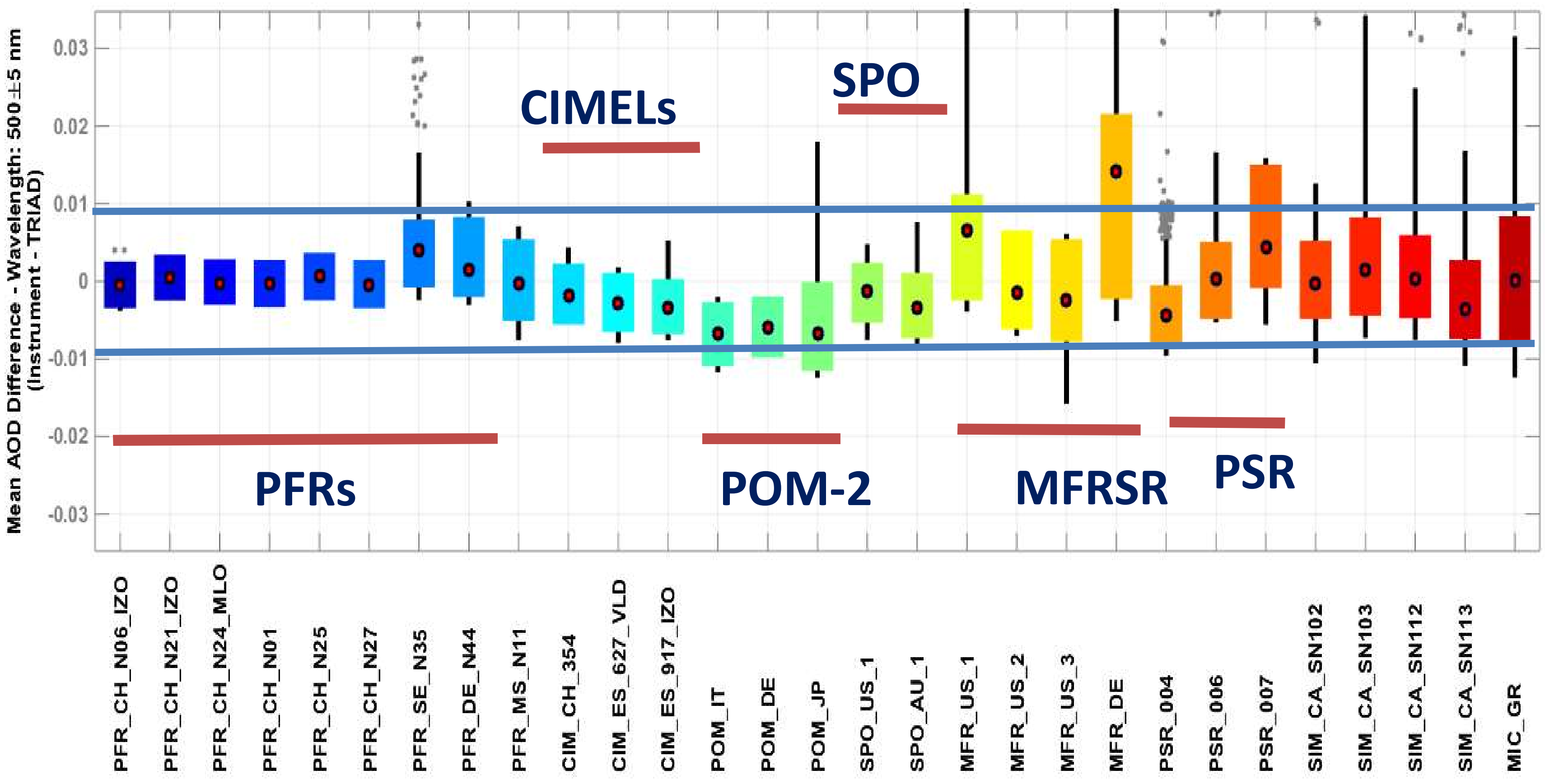
AOD differences





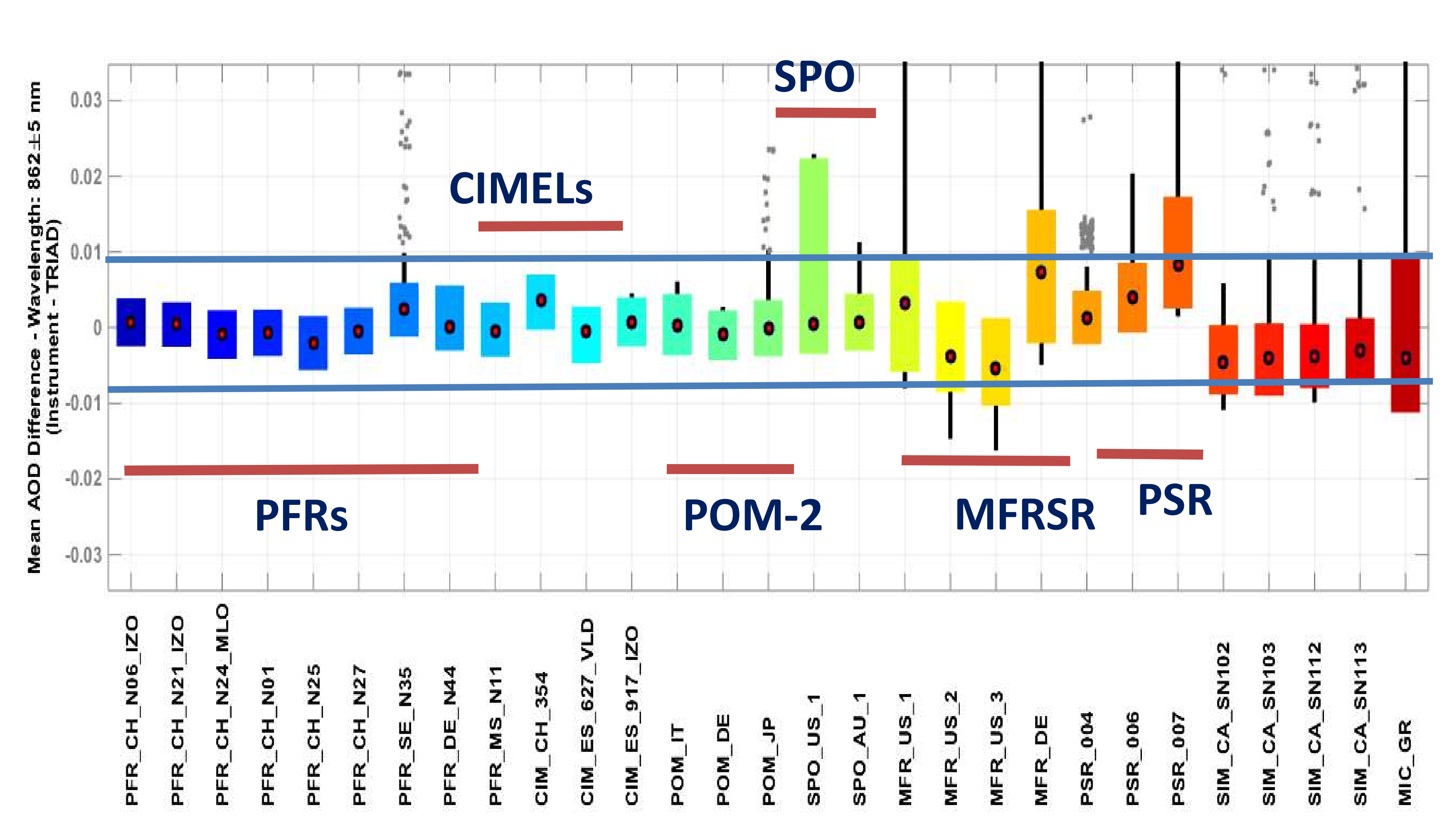
The 4th FRC results

AOD differences at 500 nm

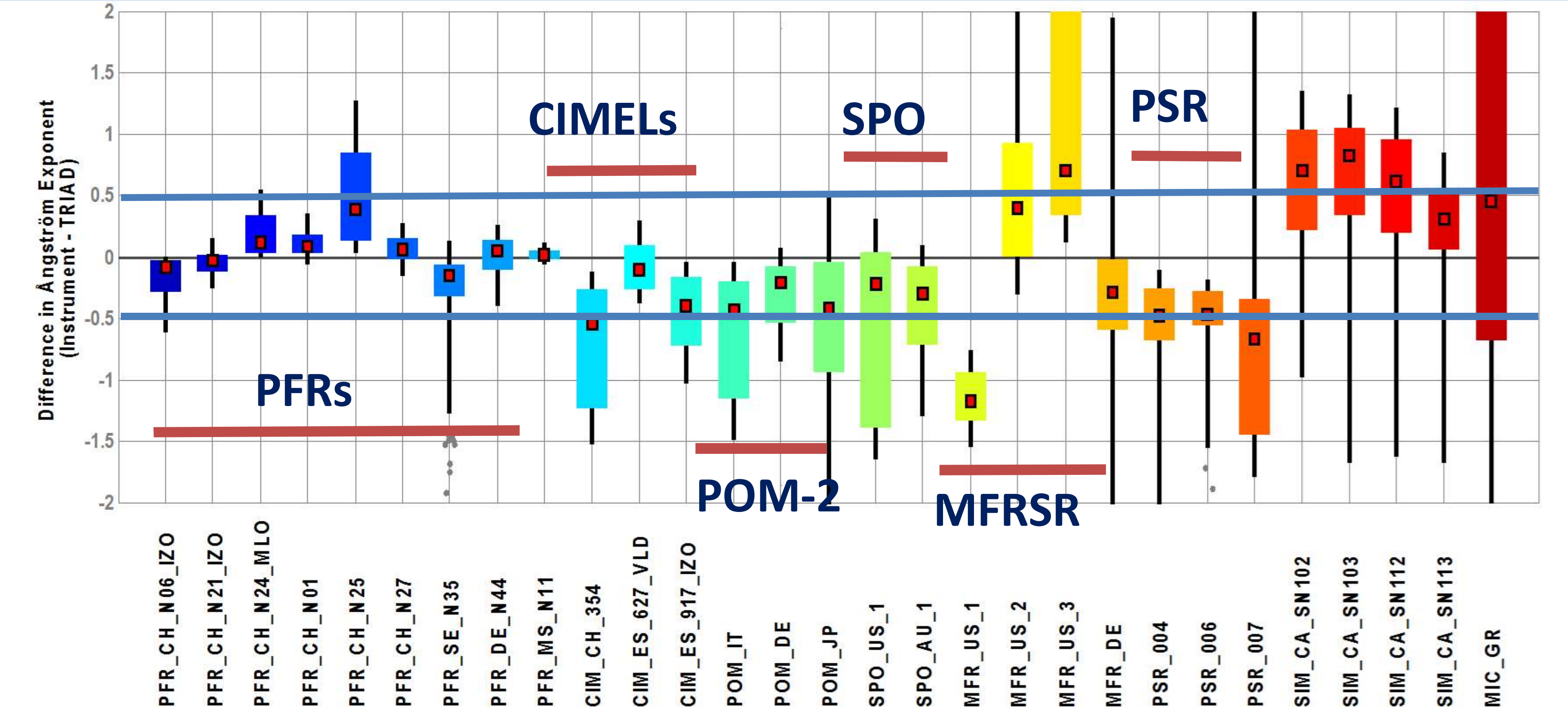


The 4th FRC results

AOD differences at 865 nm

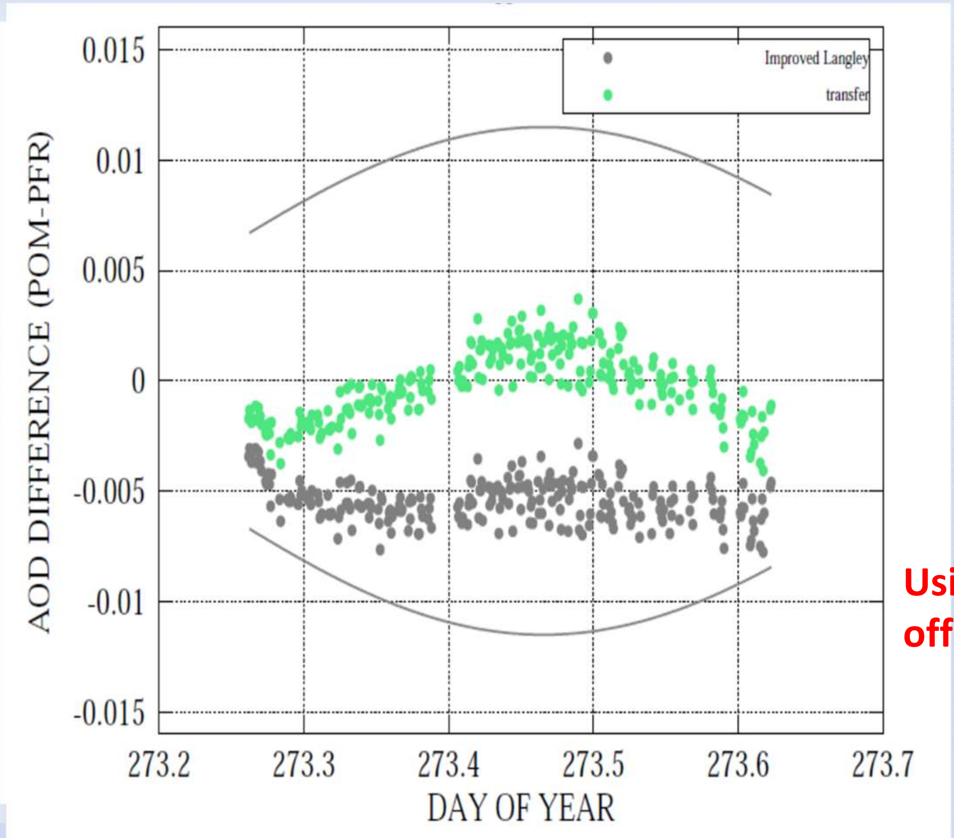


Ångström Exponents



Conclusions

- Calibration uncertainties, methods used for calibration and AOD retrieval, instrument measuring principles contribute to the observed dispersions



POM2 – triad at 500nm offset ~0.008

Using GAW-PFR algorithm offset ~0.005

Using GAW-PFR algorithm & calibration offset ~0.002

Conclusions

- Agreement for AOD at 500nm and 865nm
- Angstrom Exponent still doubtful for AOD ~0.1
- Cloud screening differences
- Processing differences (ozone, NO_2 ..)
- High AOD comparisons (field of view + issues)
- Long term comparisons
- Results could be used as a starting point for global AOD homogeneity initiatives among different Networks

WMO report

https://www.wmo.int/pages/prog/arep/gaw/documents/GAW_Report_No_231_7_Nov.pdf

Google: WMO report 231 FRC

Permanent Cimel-PFR comparison at Izaña

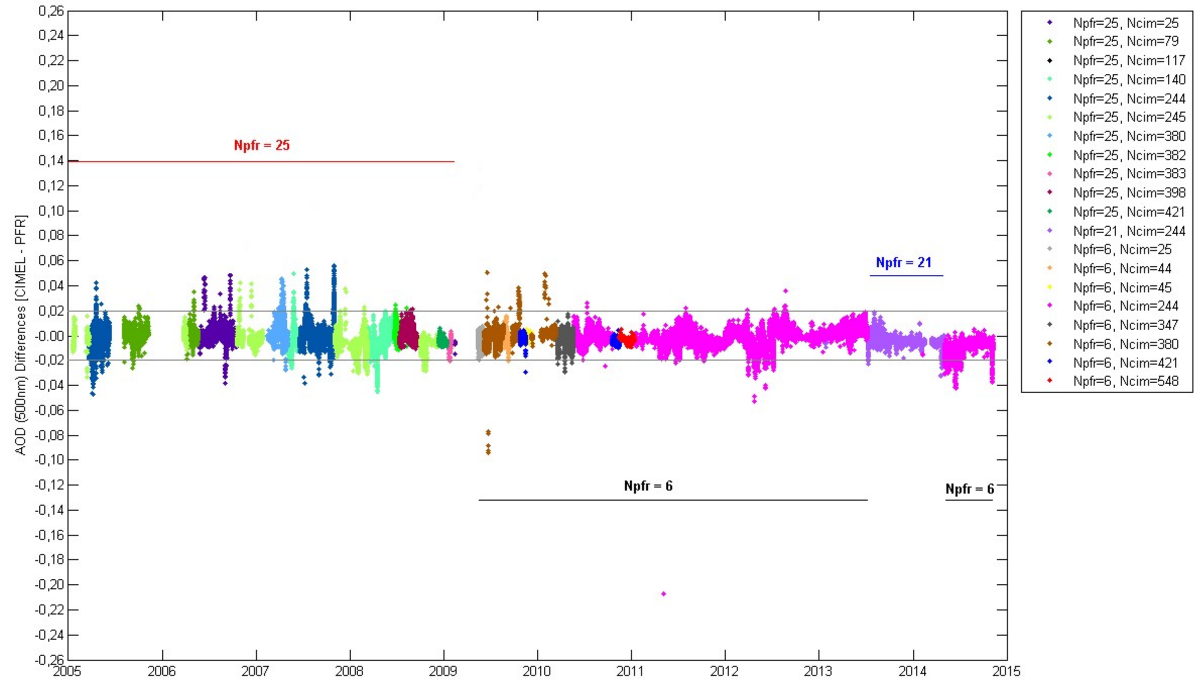
Period: from 20/01/2005 to 9/11/2014

Long-term Intercomparison Cimel/AERONET – PFR/GAW at Izaña

1’ minute simultaneous Cimel-PFR AOD data at 4 channels (2 actual channels)

15 CIMELs and 3 PFRs were used in this period

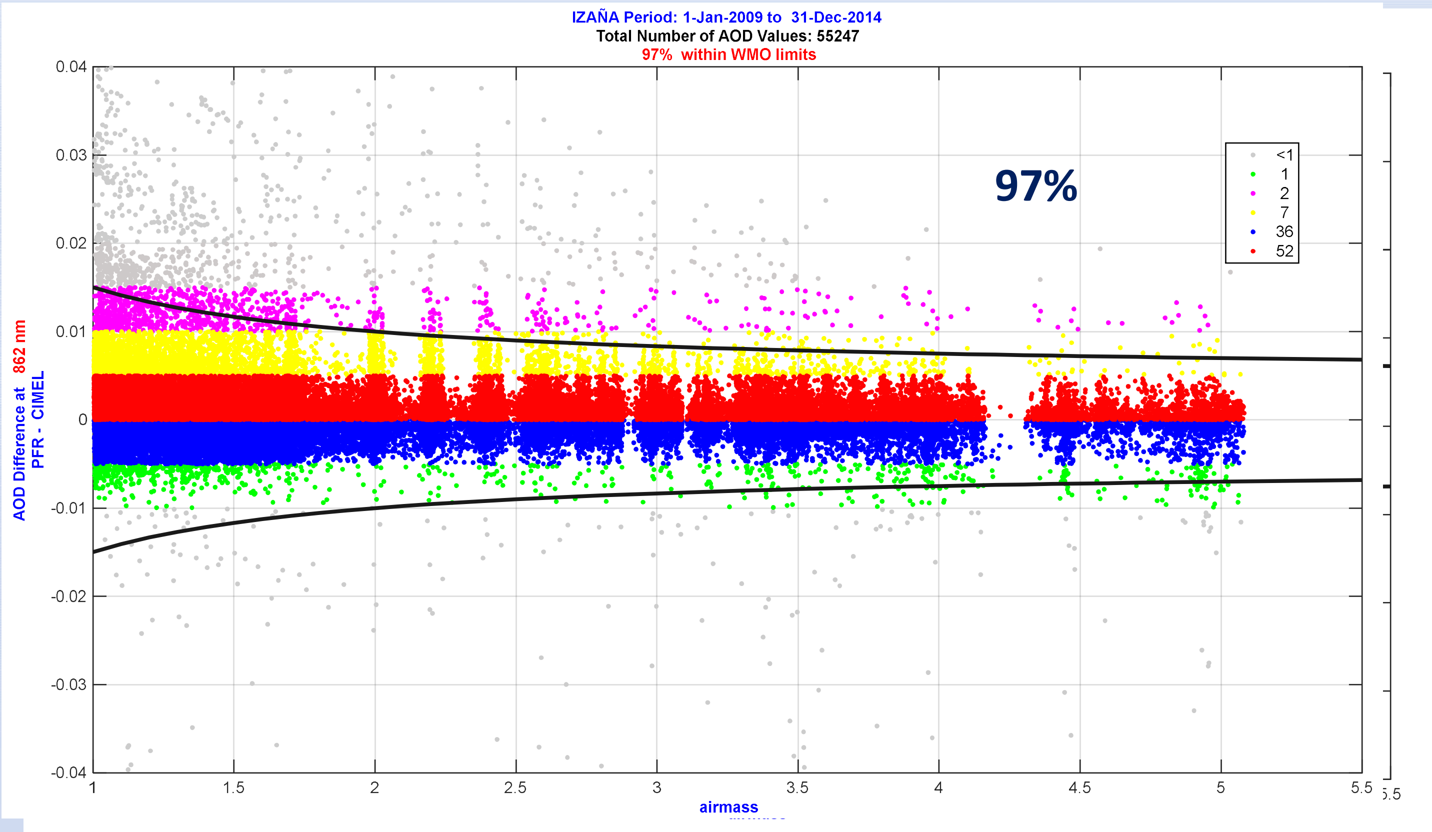
CIMELs	PFRs
25	N25
44	N06
45	N21
79	
117	
140	
244	
245	
347	
380	
382	
383	
398	
421	
548	



WORCC and AERONET / EUROPE

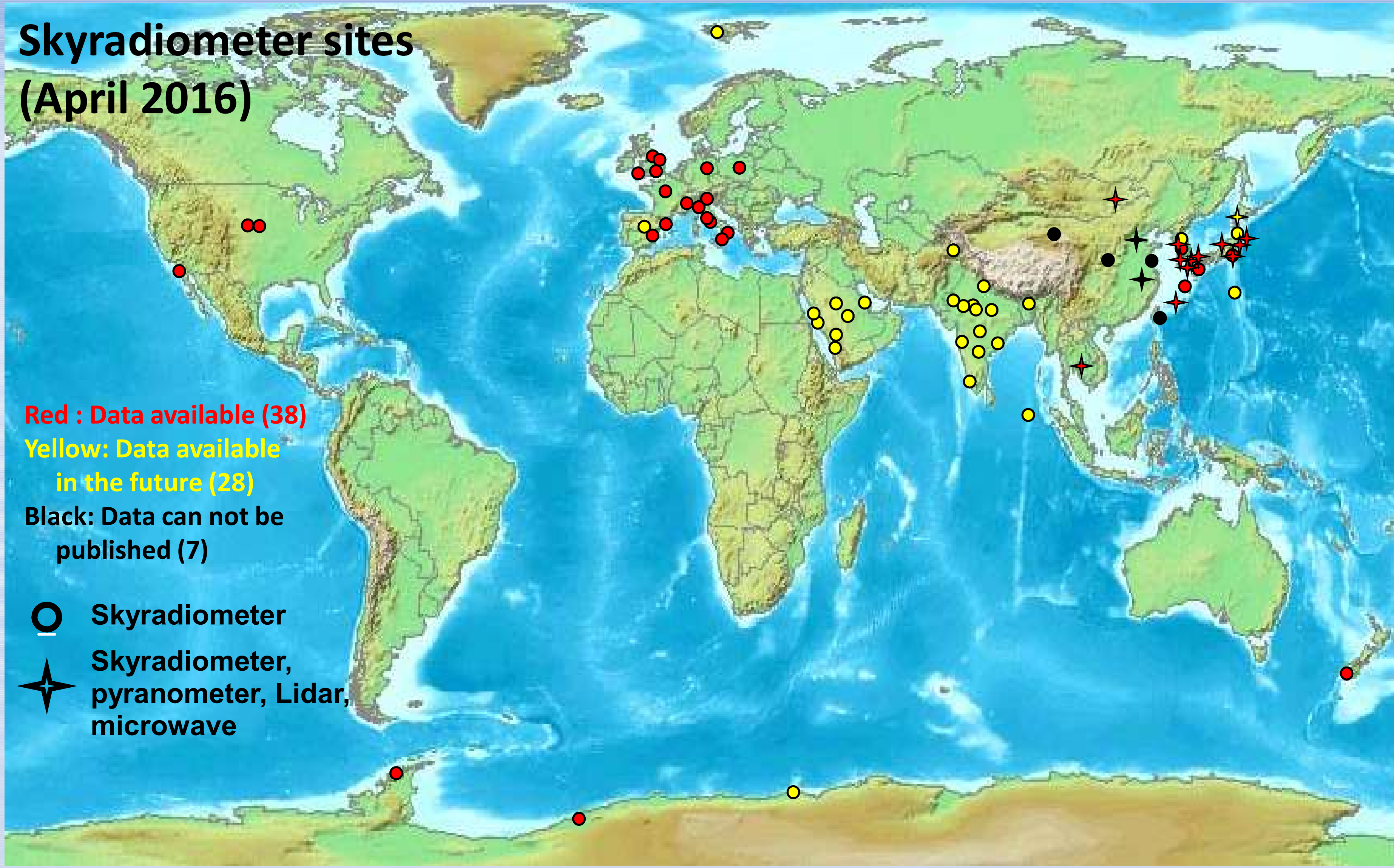
Collaboration of PMOD/WORCC with Izaña observatory:

- Langley calibration of PFRs and triad calibration transfer
- Calibration PSR, lunar PFR, UV-PFR
- Long term comparison of CIMEL and PFR
- Link long term traceability of GAW-PFR and AERONET/Europe



Romero et al., in preparation

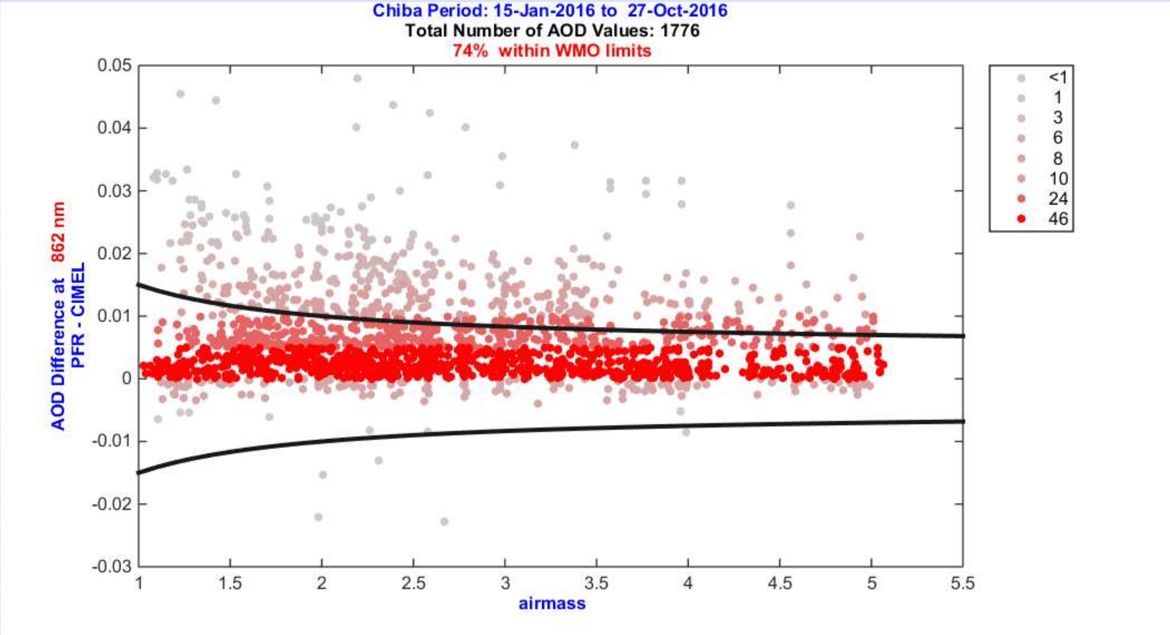
Skyradiometer sites (April 2016)

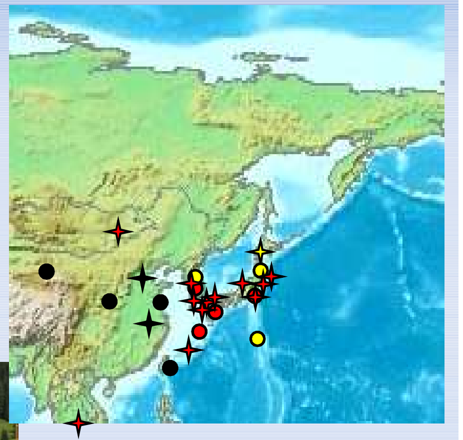


SKY-NET / POM-2 instruments: looking for permanent traceability to WORCC

Chiba – Japan: 1/2016 – today

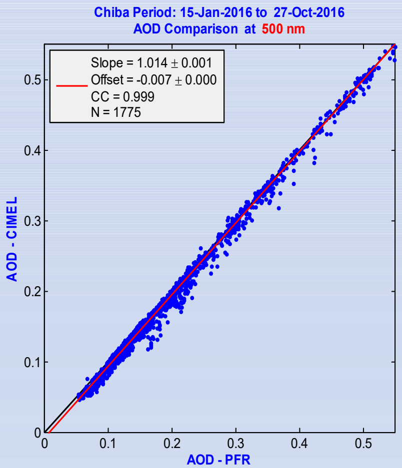
PFR vs CIMEL

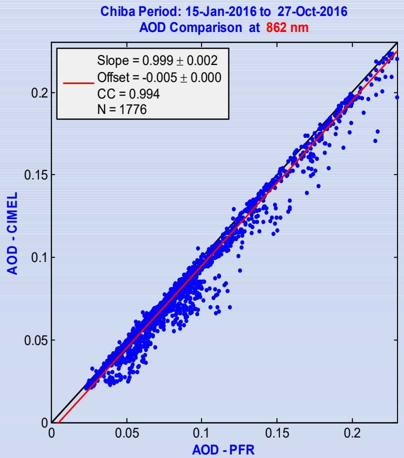




PFR

CIMEL

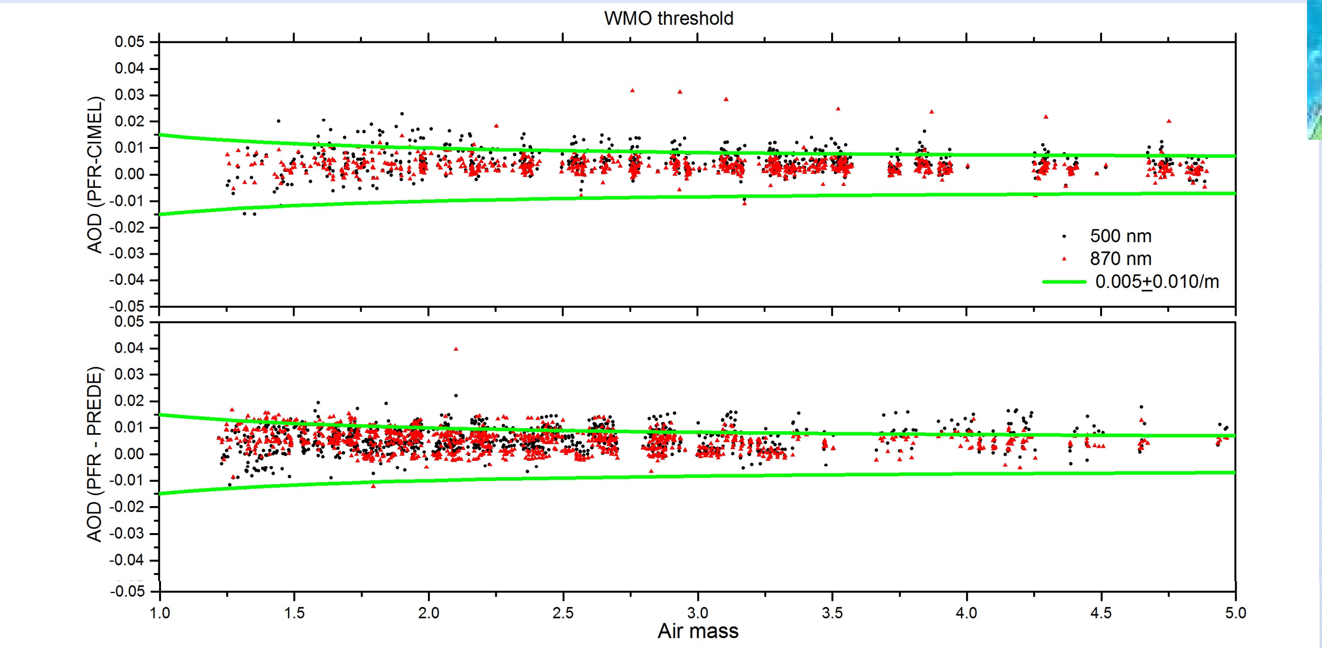


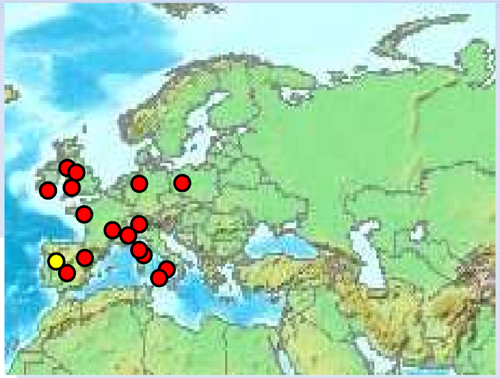


POM-2

SKY-NET / POM-2 instruments: looking for permanent traceability to WORCC

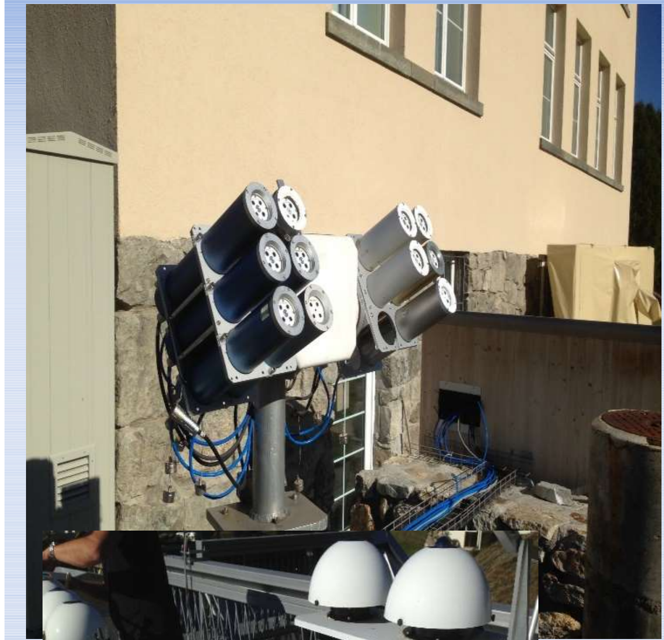
Valencia – Spain: 2/2015 – 1/2016





Campanelli, Kazadzis, et al.,: The SKYNET radiometer Network: Aerosol Optical Depth retrieval performance at the FRC-IV campaign and long-term comparison against GAW-PFR and AERONET standard instruments, WMO-TECO, 2016

Atmospheric Aerosol Eddies and Flows NASA GSFC Space Science Full HD Video.mov



Thank you