Multi Filter Rotating Shadowband Radiometer (MFRSR)

Outline

- Atmospheric radiation
  - Radiation quantities, shortwave/longwave, global energy balance and uncertainty due to aerosols
- Instruments to measure various components of atmospheric radiation
  - MFRSR
- Calculation of aerosol optical depth from radiation quantities
- Use of extinction of atmospheric radiation to calibrate solar radiometer
  - History of the Langley technique

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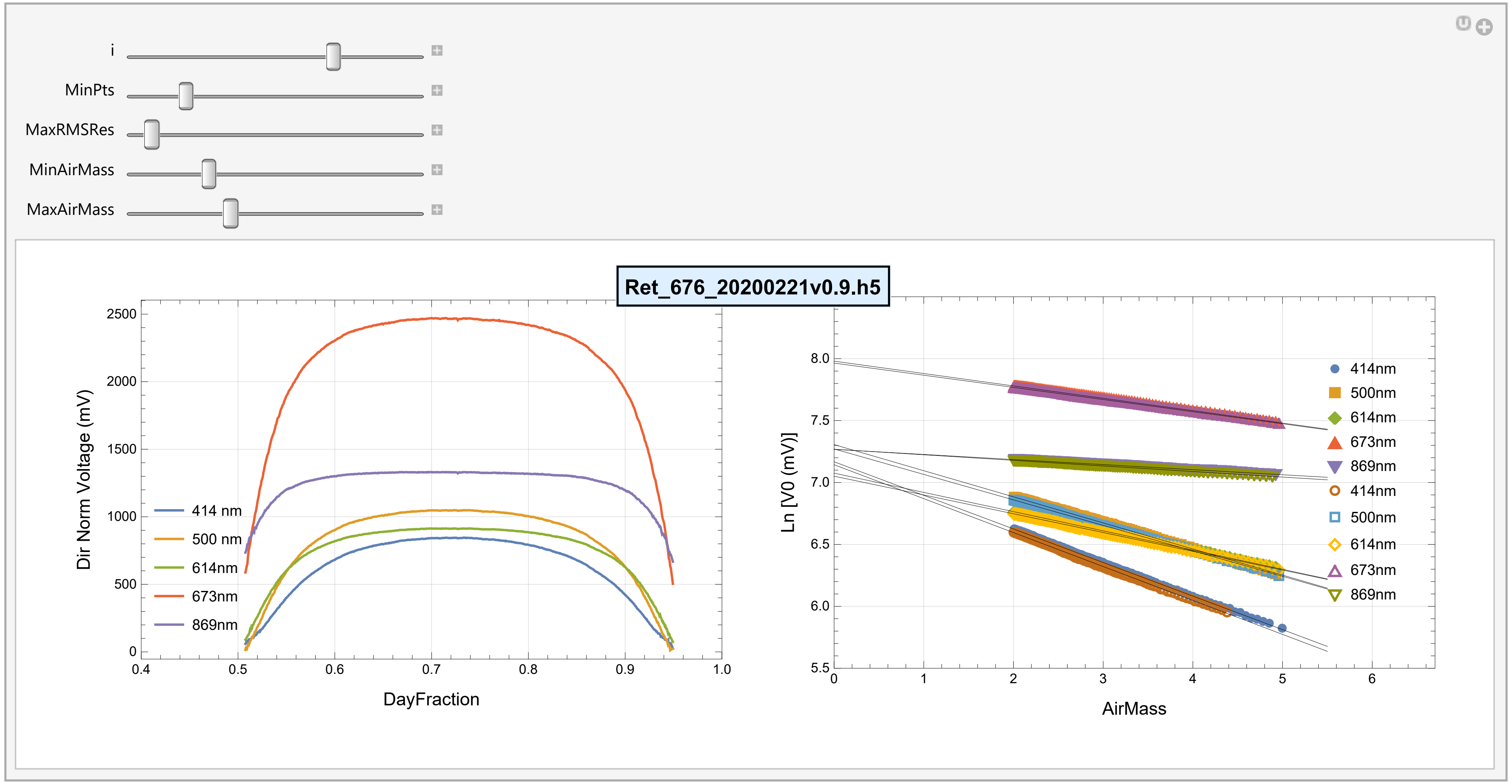

Shortwave (Solar) and Longwave (Terrestrial) Radiation and Atmospheric Transmission

- The earth is heated by shortwave radiation from the sun (~5800 K) and cools to space by radiating at the mean earth/atmosphere temperature (~255K)
  - assuming black bodies in radiative balance

Planck and Atmospheric Transmission Plot (GSFC Planetary Spectrum Generator)

TempK
LambdaMin
LambdaMax

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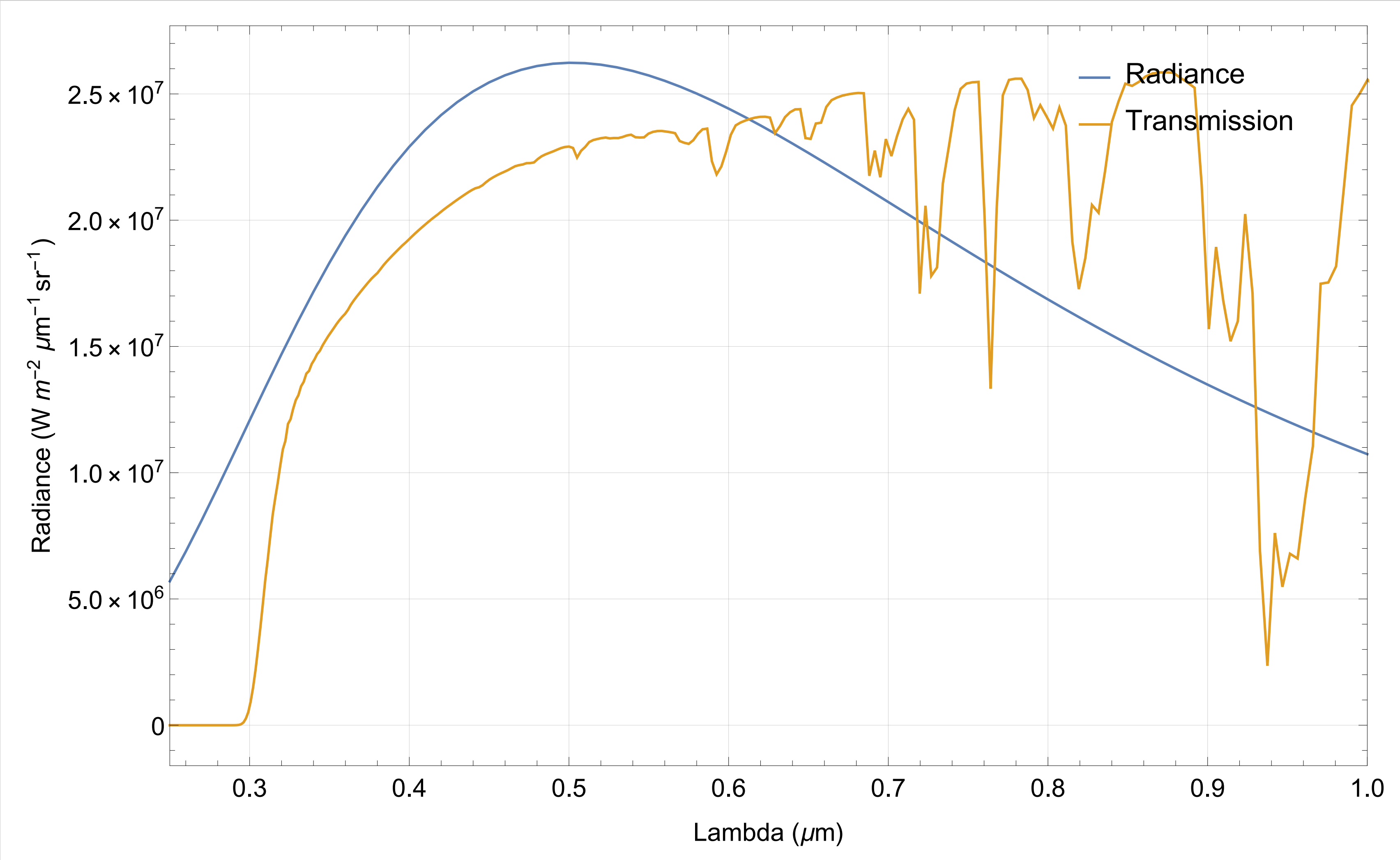


Global Energy Balance - Trenberth Diagram

Box 1 | Updated energy balance

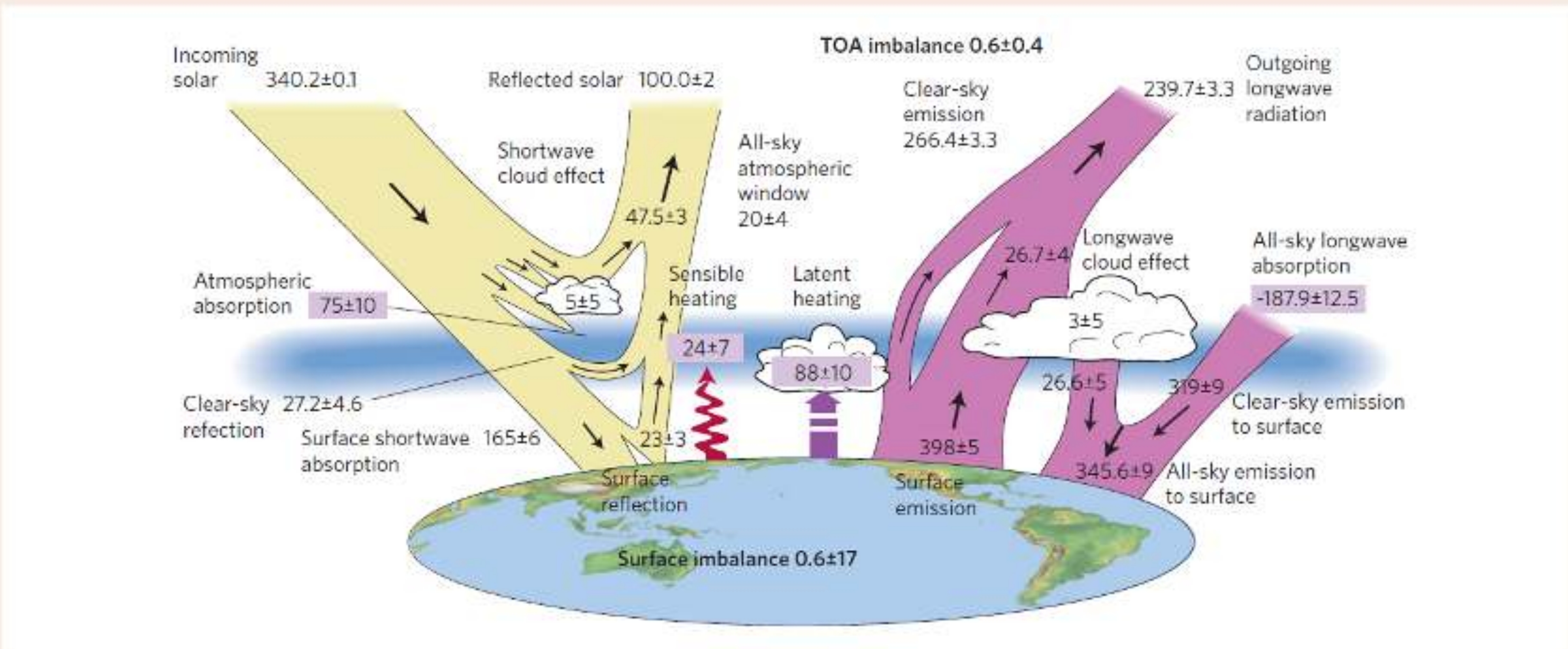


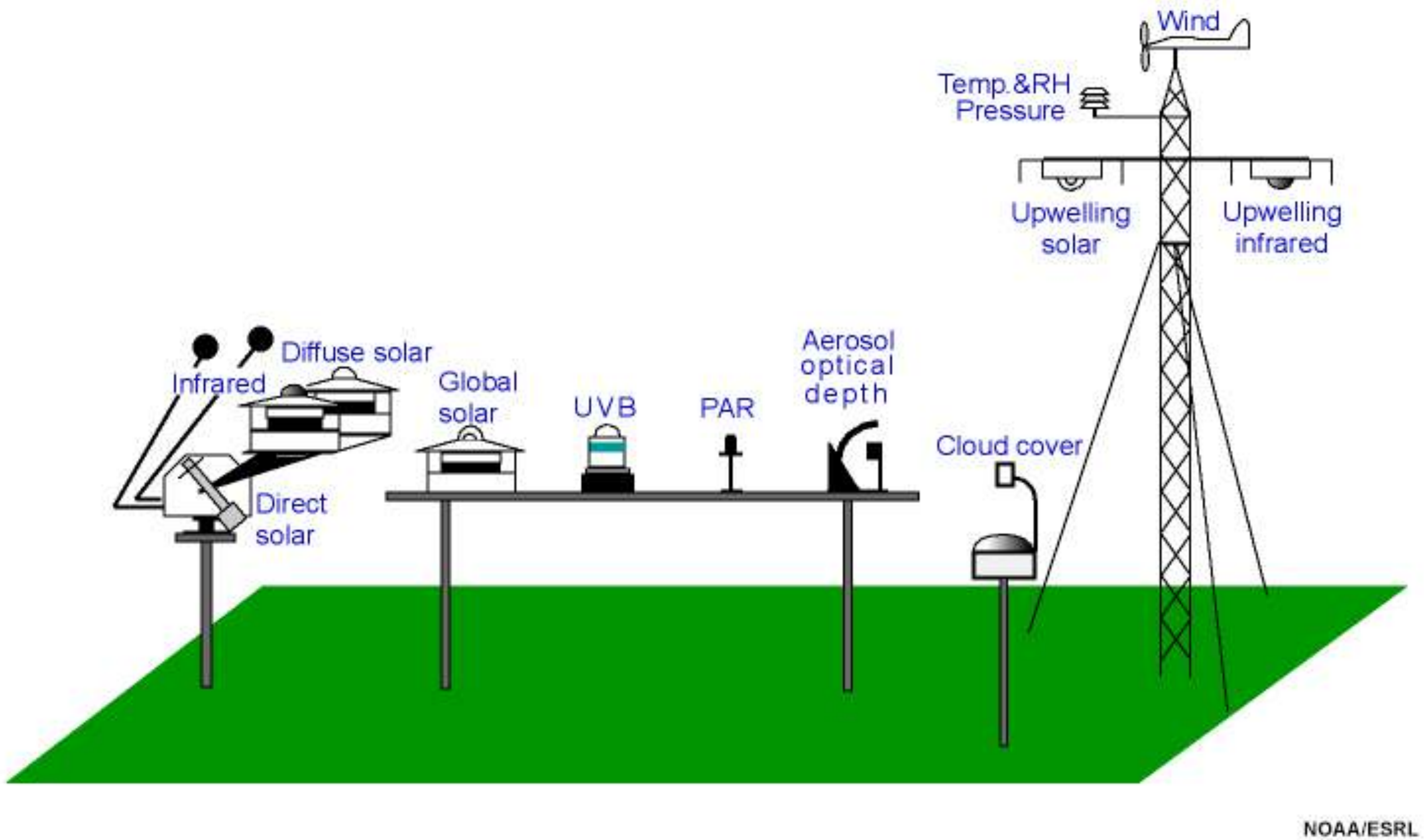
Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.

The global energy flow diagram above shows the relative values of incoming solar radiation, including reflected solar radiation. It also shows outgoing longwave radiation as well as smaller contributions of latent heating. At the top of the atmosphere, the energy balance depends exclusively on the radiative sources and sinks (namely, incoming solar, reflected solar, and outgoing longwave radiation). Other processes interact with radiative processes at Earth' s surface; the energy balance at the surface is therefore affected by other contributions (e.g., latent heat release from phase transitions and heating due to convection and conduction)

In[∘]:= *Kiehl and Trenberth (1997), Trenberth et al. (2009), Stephens et al., (2012)*

Atmospheric Radiation

- Solar energy drives atmospheric circulation and chemistry as well as interactions between the atmosphere, ocean and land.
- Satellites can measure incoming and outgoing radiation very accurately but to understand the radiation processes occuring in the atmosphere modeling based on the satellite measurements are used.
- Surface based networks have been established to monitor radiation and to provide ground based validation for satellite/modeling efforts.
  - Baseline Surface Radiation Network
    - NOAA Surfrad



- In addition to understanding atmospheric radiation processes, these radiation measurements can be used to calculate aerosol optical depth, total column water vapor, ozone and other species
  - atmospheric aerosols are primarily due to surface based sources and thus can accumulate within the boundary layer

- References
  - Baseline Surface Radiation Network (bsrn.awi.ed)
  - NOAA Surface Radiation Network (https : // www.esrl.noaa.gov/gmd/grad/surfrad/index.html)

Importance of Atmospheric Aerosols

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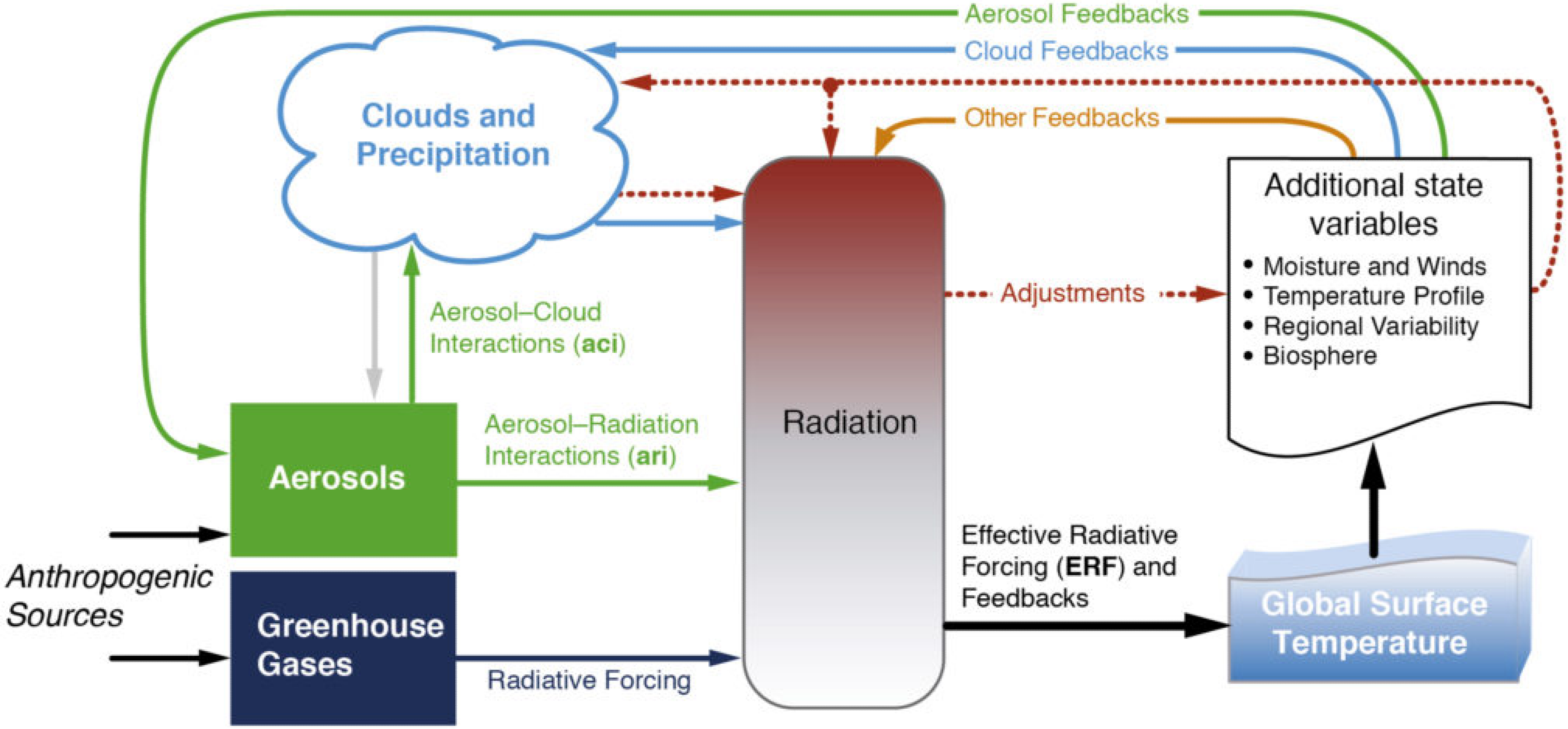

Intergovernmental Panel on Climate Change

- The total ERF due to aerosols ($ERF_{ari+aci}$, excluding the effect of absorbing aerosols on snow and ice is assessed to be -0.9 (-1.9 to -0.1) W m^{-2} with medium confidence.
- "Cloud and aerosol properties vary at scales significantly smaller than those resolved in climate models, and cloud-scale processes respond to aerosol in nuanced ways at these scales. Until sub-grid scale parameterizations of clouds and aerosol- cloud interactions are able to address these issues, model estimates of aerosol-cloud interactions and their radiative effects will carry large uncertainties." (IPCC2013)

So we need measurements on the sub-grid scale!

- What can you study with a distributed network of instruments (BSRN, Aeronet, etc)?
  - aerosol concentrations due to traffic, industries, weather, etc.
  - trends in aerosol concentrations over time
  - aerosol modification during transport
  - urban heat island effects
  - aerosol indirect effect on clouds

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L22814, doi:10.1029/2008GL036064, 2008

In[∘]:=

Surface-based observation of aerosol indirect effect in the Mid-Atlantic region

Fonya Nzeffe,[1] Everette Joseph,[1] and Qilong Min[2]

Received 18 September 2008; accepted 17 October 2008; published 29 November 2008.

Radiation Terms and Definitions

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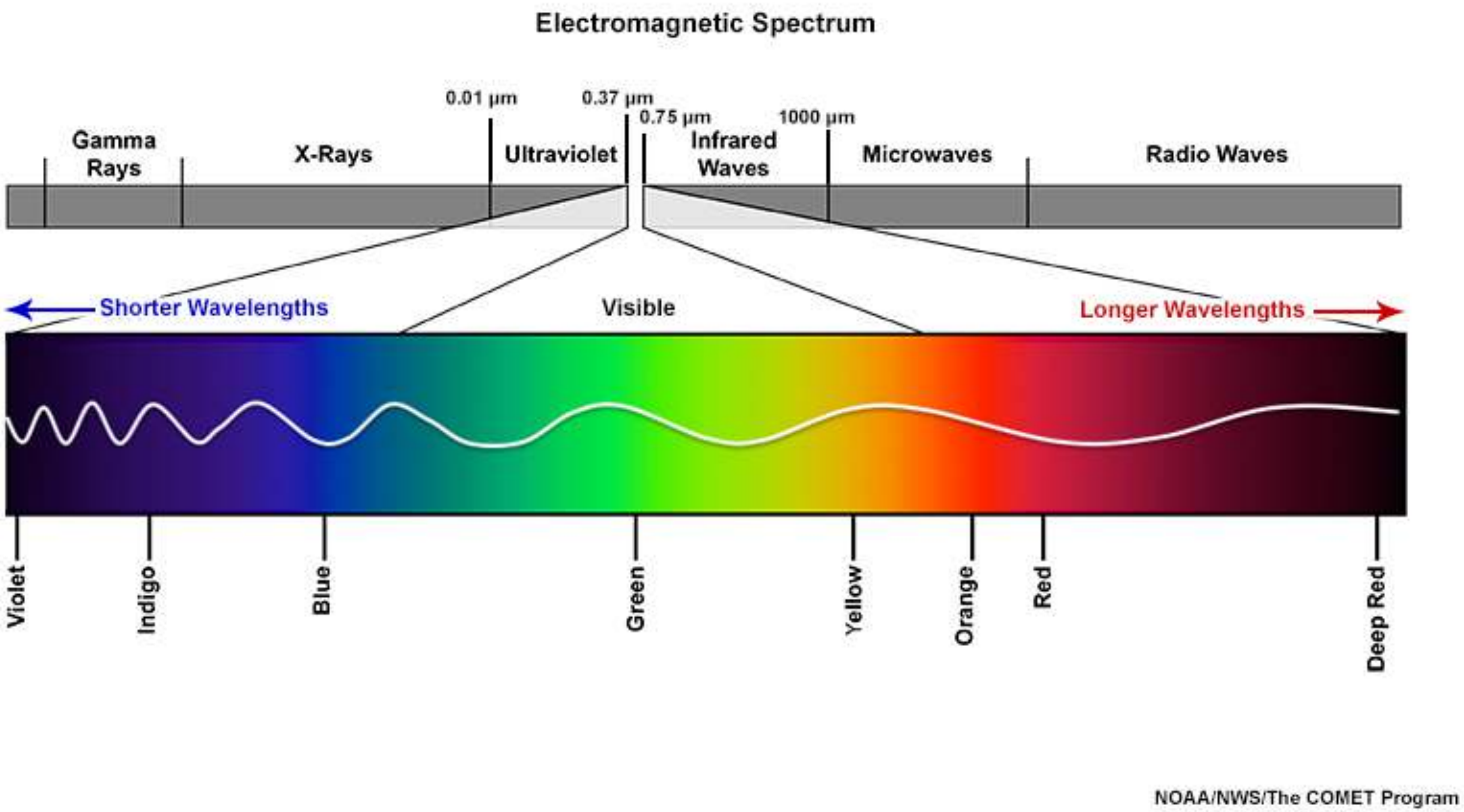

- UV (0.01 - 0.37 μm), Visible (0.37 - 0.75 μm), Infrared (0.75 - 1000 μm)
- Radiant flux - Watts (W)

Irradiance, Actinic Flux, Radiance

- Irradiance - radiant flux density through a horizontal surface (W m^{-2})
- Actinic Flux - radiant flux density through a sphere centered on the point of interest (W m^{-2})
- Radiance/intensity - rate of energy transferred through a unit area for a unit solid angle (W m^{-2} sr^{-1})
  - Note that all of these terms can also be defined spectrally resolved, e.g. W m^{-2} μm

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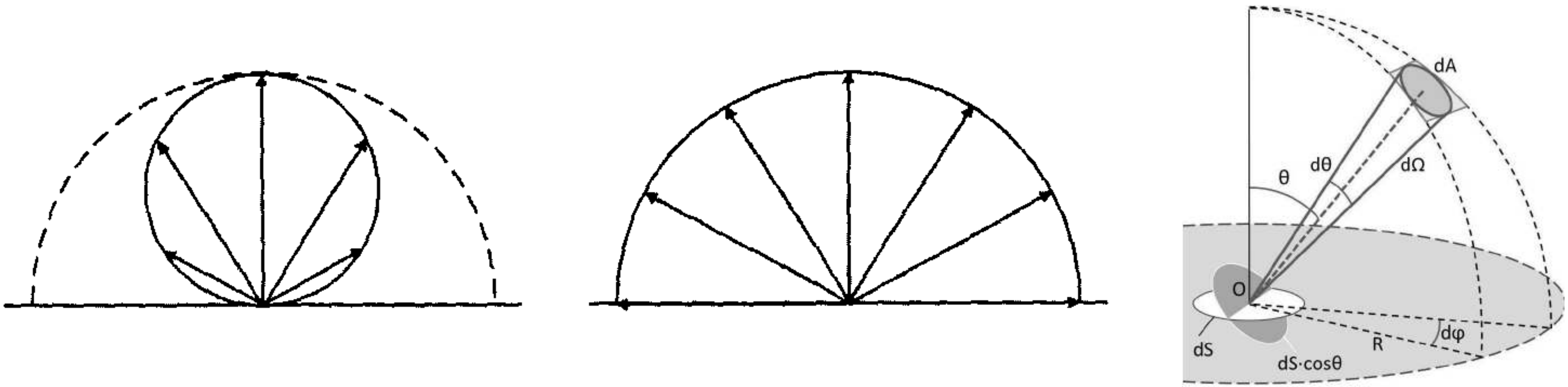
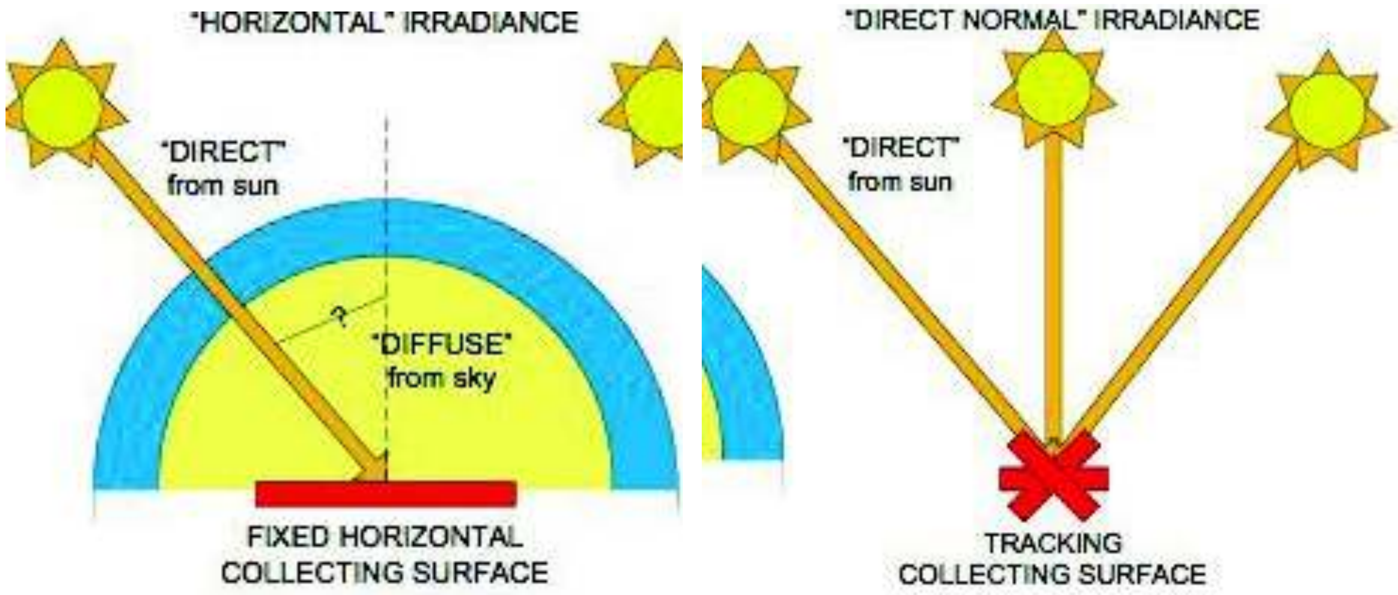


Note the difference between Total Horizontal Irradiance and Actinic Flux. **On the left** : Horizontal Irradiance is related to a horizontal detection area. Photons are weighted with the cosine of their angle of incidence. This is why a low sun provides less heat to the Earth’s surface than a high sun. **In the center** : Actinic flux density, for instance, as seen by an ozone molecule in the centre. Actinic flux density is detected isotropically, as it is of no importance to the molecule where the photons are coming from. As soon as a proper photon arrives, no matter whence, the molecule dissociates. (home.uni-leipzig.de/strahlen/web/general/en_index.php?goto=basic_quantities). **On the right**: Radiance is defined as the rate of energy transfer (W) through area dA (m^2) as a function of solid angle $d\Omega = dA / r^2$ (sr) (https://www.researchgate.net/figure-/Geometry-for-the-definitions-of-radiance-and-solid-angle_fig2_256444960)

Irradiance Terms

- Irradiance - radiant flux density through a horizontal surface (W m^{-2} or W m^{-2} μm^{-1})



- Direct Horizontal Irradiance - radiant flux through a horizontal surface due to the direct beam - no scattering effects
- Diffuse Horizontal Irradiance - radiant flux through a horizontal surface due to only to scattering effects
- Total or Global Horizontal Irradiance - sum of direct and diffuse components
- Direct Normal Irradiance - radiant flux through a surface normal to the direction of incidence

- This is the quantity that is used to calculate aerosol optical thickness

Measuring the different components of atmospheric radiation

Just a few instruments shown here ... have a look at the **Kipp and Zonen website** for many more

Shortwave (Solar) Radiation (200 - 3600 nm) - Pyranometer (e.g Kipp and Zonen CMP22)

On the right : installation at Millersville University, PA for measurement of net solar irradiance (difference between down-welling and upwelling solar irradiance)

Terrestrial (IR+) Radiation (4.5 - 42 μm) - Pyrgeometer (e.g. Kipp and Zonen CGR4)

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Direct Solar Radiation (200 - 4000 nm) - Pyrheliometer (e.g. Kipp and Zonen CHP1)

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Direct Normal, Diffuse Horizontal and Total Horizontal Irradiance - solar tracker

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SYSTEM CONFIGURATIONS

Typical Solar Monitoring System	
Sun Tracker	
Shading Ball Assembly	
Pyrheliometer	direct solar radiation
Pyranometer	global solar radiation
Pyranometer (shaded)	diffuse solar radiation
Data Logger	

Consider the use of the Sun Tracker for ...

- Comparing the intensity of the direct, diffuse and global components of irradiance
  - The measurements of the pyrheliometer and the two pyranometers must be compared. They are high quality instruments **but** each instrument possesses a certain amount of calibration uncertainty which increases the total uncertainty budget of the comparison.
- Calculating albedo by comparing the intensity of the direct and diffuse irradiances
  - the magnitude of the diffuse irradiance is strongly a function of the surface albedo. The ratio, therefore, of diffuse/direct irradiance can be used to determine the local surface albedo **but** again the different calibrations of the two instruments used increases the total uncertainty of the ratio.
- *Wouldn't it be nice* if you could make these kinds of measurements without the

issue of differing calibrations among the two or three instruments needed for the individual measurements?

Multi Filter Rotating Shadowband Radiometer

Major advance: offers spectrally resolved total, diffuse and direct irradiance measurements all with identically the same calibration

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Setup of MFRSRs at HU Beltsville in Nov, 2018

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Then UMBC undergrad and NCAS - M student, Wambugu Kironji, works on the interface boxes for the MFRSRs being set up on the roof of the main building at HU Beltsville. The setup requires high accuracy in pointing (toward geographic south), leveling, timing. When operating the rotating band alternatively shadows in three positions as shown.

A bit of MFRSR History …

- MFRSRs were invented starting in the late 1980s by Lee Harrison (Atmospheric Science Research Center, U. Albany) and Joe Michalsky (then at ASRC, now NOAA Emeritus) due to the research supported under the Department of Energy's IDP (Instrument Development Program), the precursor to the DOE ARM (Atmospheric Radiation Measurements) program
- ASRC licensed the MFRSR to Yankee Environmental Systems (YES) in Massachusetts for production and several hundred have been used around the world
  - Standard instrument at ARM sites and in the NOAA SurfRad network
- Over the years both NOAA and ARM modified the original MFRSR processing software or data logger but the head components still remain the Yankee product.
- We have the original Yankee hardware and software

MFRSR Details

Automated solar radiometer measuring spectrally resolved total horizontal irradiance, diffuse horizontal irradiance and direct normal irradiance ($W\ m^{-2}\ \mathrm{nm}^{-1}$)

By measuring diffuse, total and (by subtraction) direct irradiance using the same optical path and detectors the calibration of all these measurements is identically the same.

- Wavelength bands (~10 nm widths)
    - 414, 500, 614, 673, 869, 938 (W m^{-2} nm^{-1})

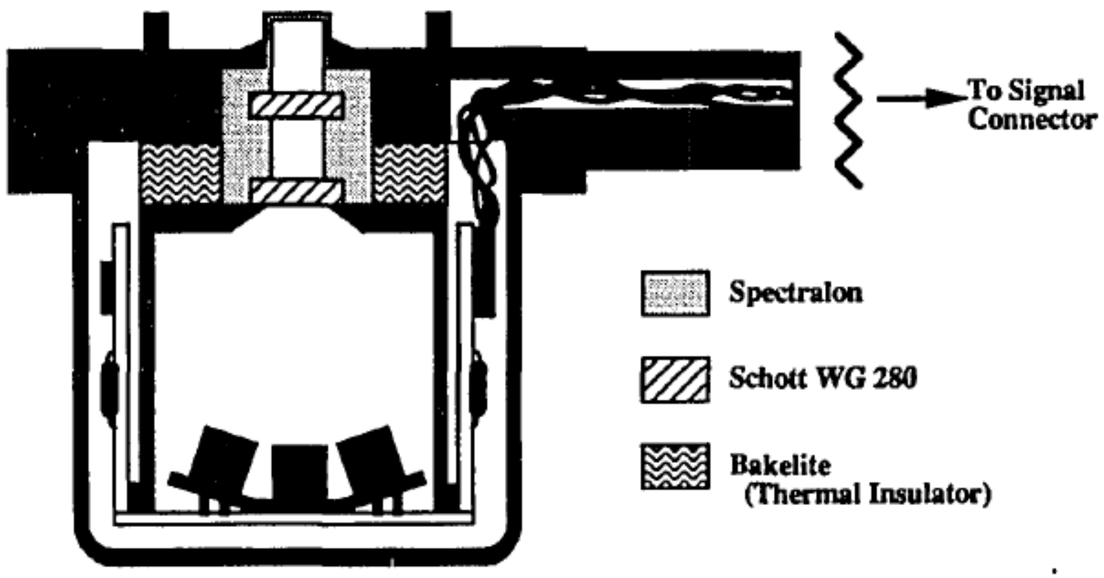

Fig. 2. Multifilter detector cross section (not to scale).

With the shadow band covering the diffuser as shown on the right, the MFRSR measures diffuse irradiance. The total irradiance is measured when the band is completely at the bottom of its rotation. The measurements taken at the two positions on either side of that shown above provide data for compensating for the effects on the diffuse measurements of the additional shading of the shadow band itself.

Angular Correction Function

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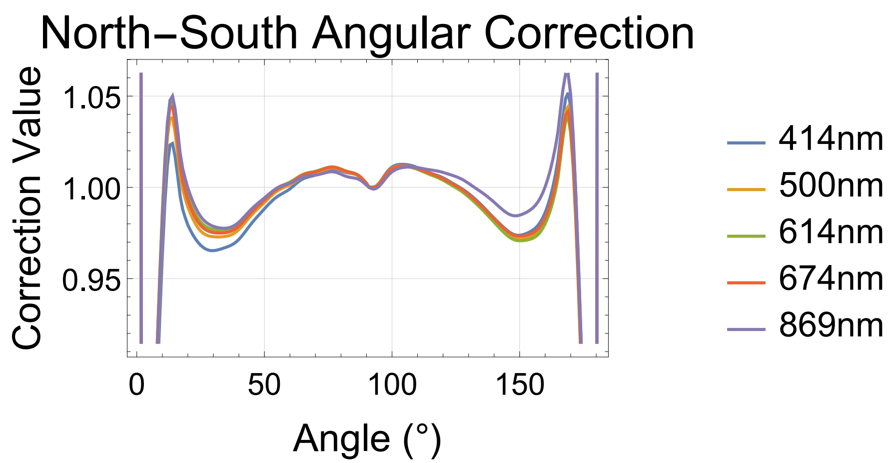

Note that, as opposed to a pyrheliometer which tracks the sun and is always measuring normal to the incident beam, the MFRSR measures with a horizontal diffuser and thus at varying incidence angles. The efficiency of diffusing light down the optical path to the detectors varies as a function of incidence angle and must be calibrated. The correction is in general a few percent although can reach quite high values for very low incidence angles. Very low angle measurements are often neglected to avoid this issue.

NB! this correction has already been applied to the voltage data that you will be working with. You don’t have to make this correction.

How well do they work?

Surface radiation standard instrument but maintaining an identical calibration for all measurements presents trade - offs.

S. Kazadzis et al.: Results from the Fourth WMO Filter Radiometer Comparison **3191**

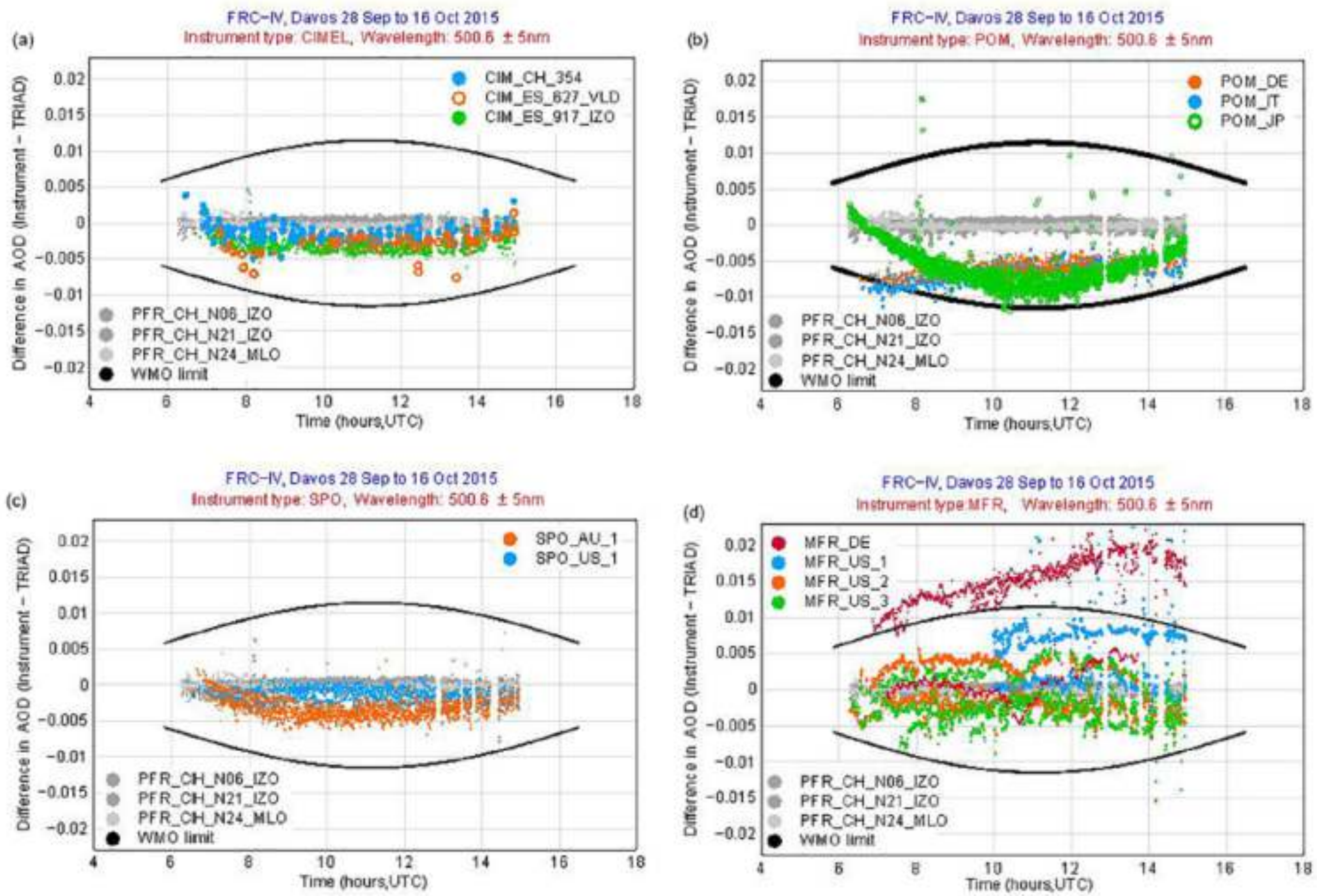

Figure 2. Comparison of the triad (gray points) with the Cimel instruments (**a**, 500 ± 5 nm), POM instruments (**b**, 500 ± 5 nm), SPO instruments (**c**, 500 ± 5 nm) and with the MFR instruments (**d**, 862 ± 5 nm). Different colors represent different instruments for all the five comparison days, and gray lines represent the WMO AOD limits.

From Kasadzis et al., ACP, 2018

Beer-Lambert-Bouguer Law and the calculation of aerosol optical thickness

$$\mathrm{I}(\mathrm{x}) = \mathrm{I}_0\, \mathrm{e}^{-\tau\, \mathrm{x}}$$

where I_0 is the irradiance at x=0, τ is the extinction coefficient (L^{-1}) and τ x is the optical depth (unitless)

Other than aerosols and molecular scattering, what are the significant components of τ in the in the spectral region of the MFRSR?

Look at output from NASA/GSFC Planetary Spectrum Generator (psg.gsfc.nasa-.gov)

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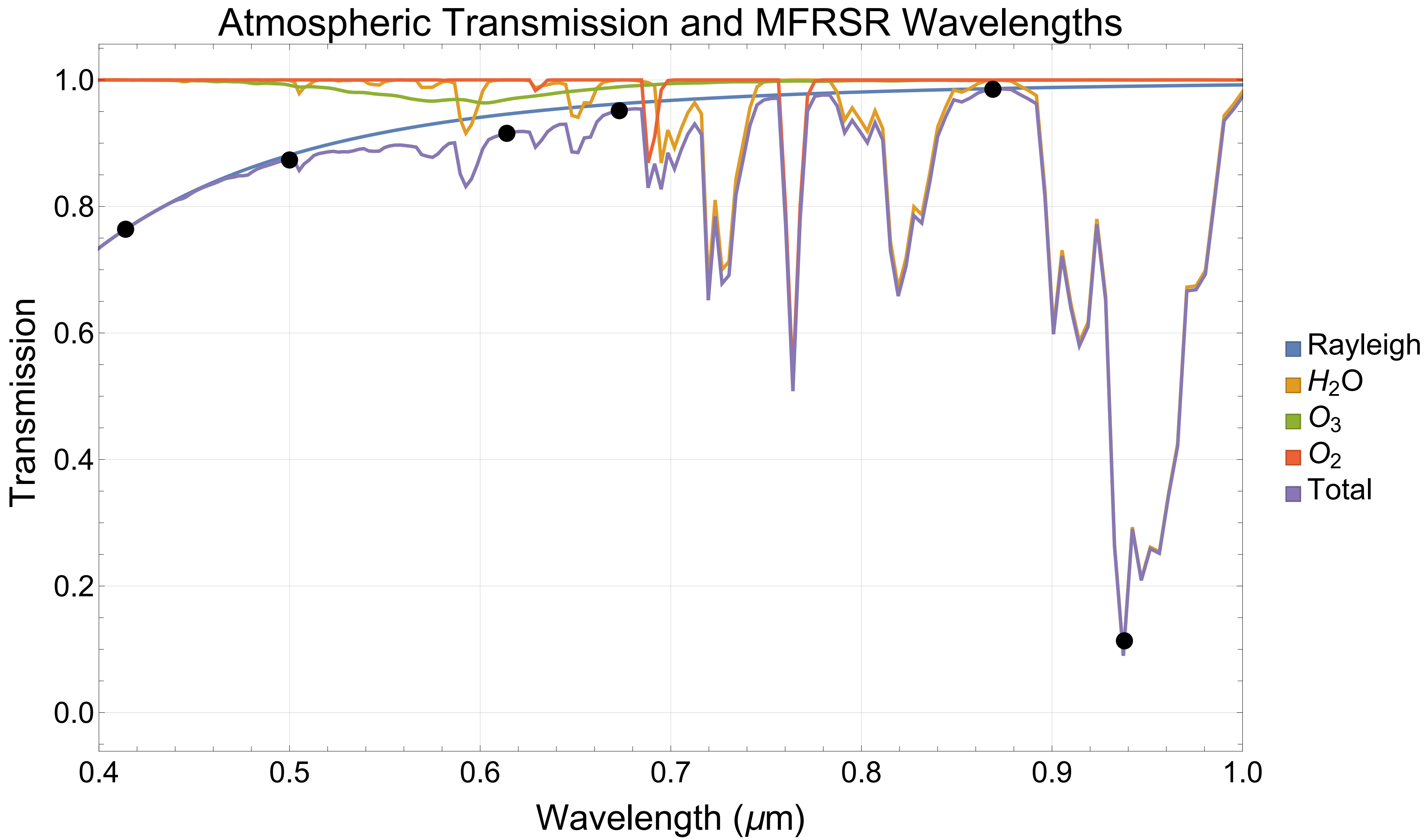

Significant Components of τ

$\tau_{\text{total}}(\lambda) = \sum_i \tau_i(\lambda) = \tau_{\text{ray}}(\lambda) + \tau_{\text{aer}}(\lambda) + \tau_{o_3}(\lambda) + \tau_{h_2\,o}(\lambda)$

So for an instrument that is looking through the total atmospheric column Beer' s Law becomes

$$I_{\text{MFR}}(\lambda) = I_0(\lambda)\, e^{-(\tau_{\text{ray}}(\lambda)+\tau_{\text{aer}}(\lambda)+\tau_{o_3}(\lambda)+\tau_{h_2\,o}(\lambda))\, M(\theta)} \qquad (1)$$

where,

I_{MFR} = Irradiance at the MFRSR $(\text{W m}^{-2}\,\text{nm}^{-1})$

I_0 = Top of the atmosphere solar irradiance

$M(\theta)$ = total # of airmasses as a function of elevation

τ_i = optical depths for 1 airmass

How to Calculate Aerosol Optical Thickness?

From Eq 1 :

$$\tau_{\text{aer}}(\lambda) = \frac{\text{Ln}[I_{\text{o}}(\lambda) / I_{\text{MFR}}(\lambda)]}{M(\theta)} - \tau_{\text{ray}}(\lambda) - \tau_{o_3}(\lambda) - \tau_{h_2\,o}(\lambda)$$

Now one of the beautiful aspects of this technique can be seen. Let's assume that the calibration of the irradiance is off by a factor of α and that $I_{\text{o}}(\lambda)$ has been determined from MFR measurements. Since $\text{Ln}[\alpha \text{I}_{\text{o}}(\lambda) / \alpha \text{I}_{\text{MFR}}(\lambda)] = \text{Ln}[I_{\text{o}}(\lambda) / I_{\text{MFR}}(\lambda)]$ you get the same result for $\tau_{\text{aer}}(\lambda)$. So in fact, calibrated irradiances are not needed to calculate AOD!

And given that the calibration is regularly changing as can be seen from this analysis, for the calculation of AOD it is best to work with the raw voltages of the instrument. Then any changes in gain or offset in the electronics used for the measurements that could affect the conversion of voltage to irradiance do not influence the calculation of AOD. So to calculate AOD we use:

$$\tau_{\text{aer}}(\lambda) = \frac{\text{Ln}[V_{\text{o}}(\lambda) / V_{\text{MFR}}(\lambda)]}{M(\theta)} - \tau_{\text{ray}}(\lambda) - \tau_{o_3}(\lambda) - \tau_{h_2\,o}(\lambda) \quad (2)$$

Rayleigh optical depth, $\tau_{\text{ray}}(\lambda)$, can be calculated accurately knowing the surface pressure. Ozone optical depth, $\tau_{o_3}(\lambda)$, adds little to the total optical depth so calculations of ozone optical depth based on climatology are generally good enough. We will avoid the 869 nm for calculations of AOD since water vapor absorbs strongly at this wavelength and is too highly variable to extract AOD.

But how to calculate M(θ) and Ln[$V_{\text{o}}(\lambda)$]?

Calculating the AirMass and calibration constant Ln[$V_o(\lambda)$]

Essentially everybody in the world (except Aeronet/GSFC) uses only Langley regressions at high elevation places to derive a calibration

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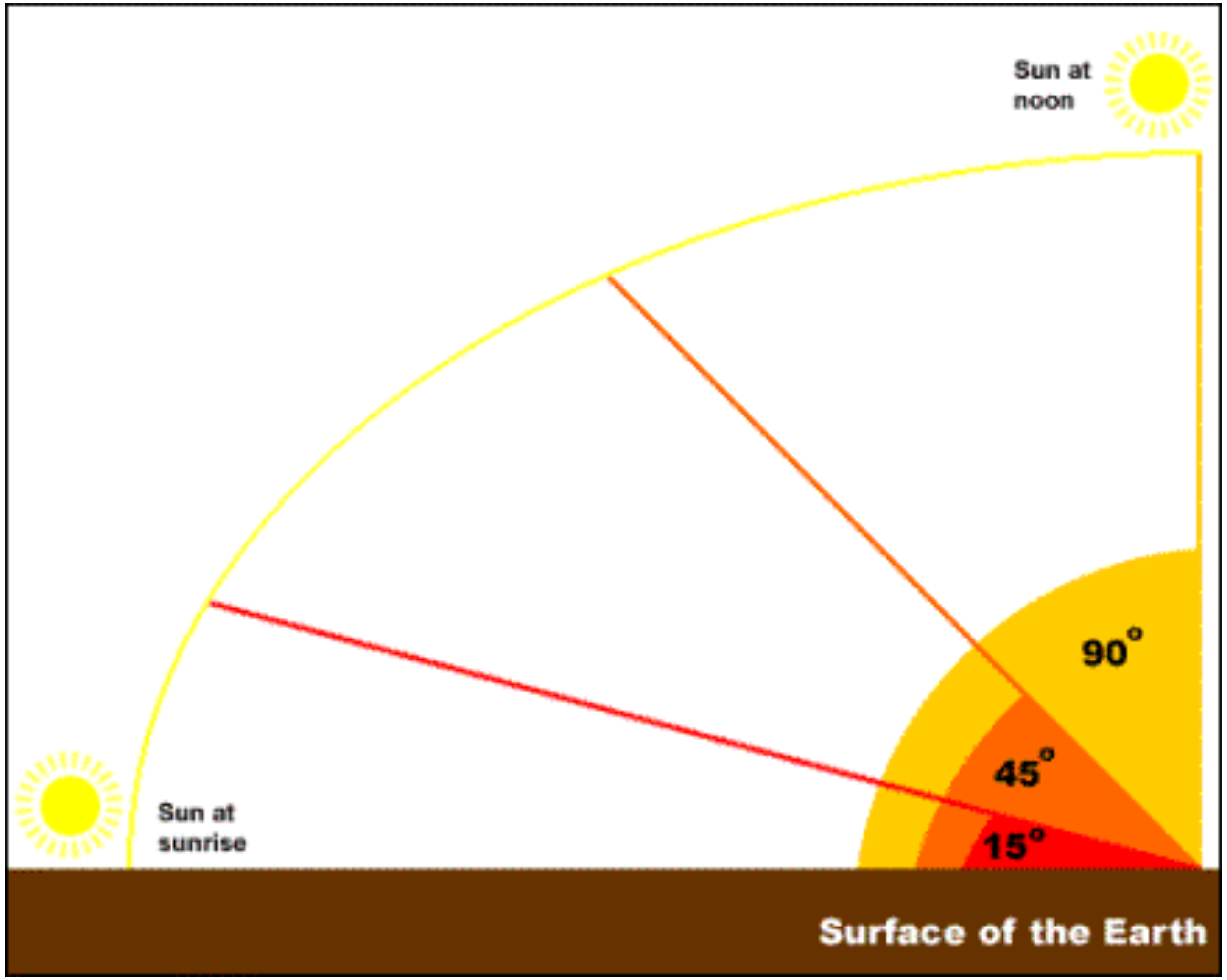

Assuming horizontal homogeneity and an unchanging atmosphere over a morning or afternoon ...

Recalling equation 1 but, based on the preceding argument, using voltages instead of irradiance (and dropping the λ's but never forgetting them...)

$$V_{\mathrm{MFR}} = V_0\, e^{-(\tau_{\mathrm{ray}}+\tau_{\mathrm{aer}}+\tau_{O_3}+\tau_{h_2\,o})\,M(\theta)}$$

and taking the natural log of both sides

$$\mathrm{Ln}[V_{\mathrm{MFR}}] = -M(\theta)\,(\tau_{\mathrm{ray}}+\tau_{\mathrm{aer}}+\tau_{O_3}+\tau_{h_2\,o}) + \mathrm{Ln}[V_0]$$

- This is a linear equation (y = m x + b) which gives $\mathrm{Ln}[V_{\mathrm{MFR}}]$ as a function of
  - $M(\theta)$, independent variable giving the airmass amount
  - $-(\tau_{\mathrm{ray}}+\tau_{\mathrm{aer}}+\tau_{O_3}+\tau_{h_2\,o}) = -\sum \tau_i$, the slope which gives the total optical depth
  - $\mathrm{Ln}[V_o]$, the y intercept

How to calculate the airmass?

- From Kasten (1965), Kasten and Young (1989)

In[ ]:=

$$f(\gamma) = [\sin\gamma + a\cdot(\gamma+b)^{-c}]^{-1}, \quad (3)$$

values are: $a = 0.50572$, $b = 6.07995°$, $c = 1.6364$. These

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AirMassElevAngles[MFRElevAngles_] := Module[{},
   (Sin[MFRElevAngles Degree] + 0.50572 (6.07995 + MFRElevAngles)^-1.6364)^-1
  ]
```

But first ... why are these called Langley regressions?

- Samuel P. Langley was an astronomer and inventor and studied the sun intensely.
  - Textbook on astronomy called "The New Astronomy" in 1887
    - Hand drawn pictures of sun spots.
  - Considerable effort in attempting to calculate the solar constant using what we now call the Langley technique.
  - Founder of the Smithsonian Astrophysical Observatory in 1890s
  - Inventor in 1890s of heavier-than-air aircraft.
    - NASA/Langley Research Center in Hampton, VA is named in honor of this work in aviation.

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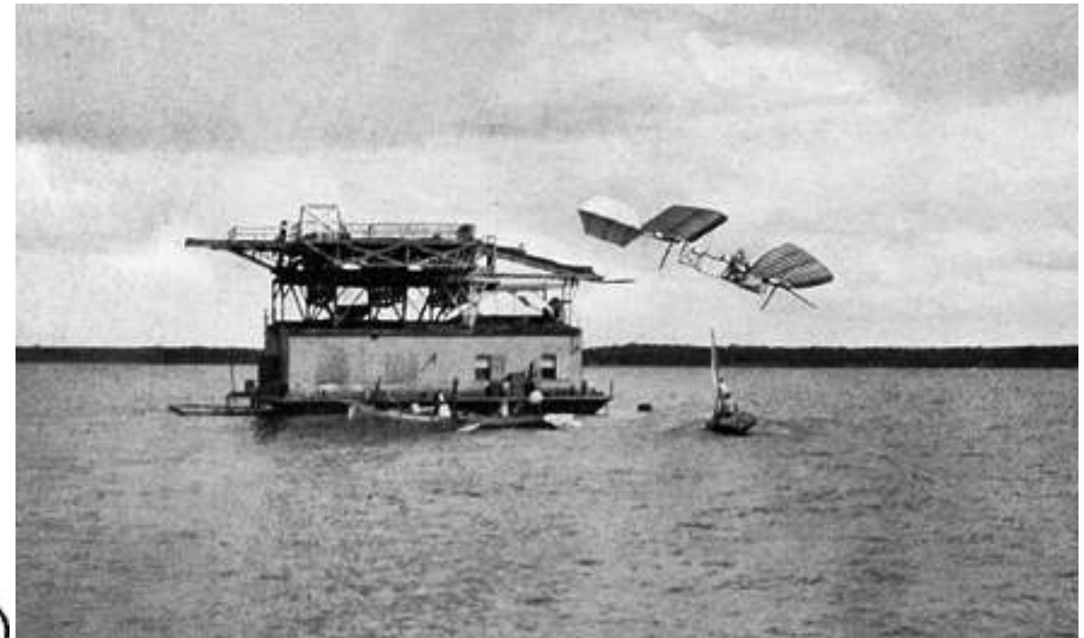
FIG. 19. — TYPICAL SUN SPOT OF DECEMBER, 1873.
(REDUCED FROM AN ORIGINAL DRAWING BY S. P. LANGLEY.)



OK, but did Langley invent the technique? Not really ...

Exponential extinction of light and the concept behind Langley plots first described by Pierre Bouguer in lectures in ~1750. About a decade later, Johann Lambert published the same ideas in latin. Bouguer is also invented the heliometer, which permitted the relative luminous intensity of objects to be quantified.

In[ ]:=

Fig. 11.

VARIOUS MEANS OF MEASURING LIGHT 65

ARTICLE IX

To find how much the light of celestial bodies increases or decreases with the changes in their altitudes above the horizon

THIS OBSERVATION cannot be made with equal facility on all the heavenly bodies. The light of the stars is too weak, and that of the sun is, on the contrary, too strong, to allow them to be compared conveniently with the different sources of light which we have here below. That is why one can hardly make this observation except on the moon. But we have also to take this planet when it is almost in opposition with the sun; its phase then changes only very slightly, and one may be sure that practically all the change in its light will come from its different altitudes above the horizon. After that the operation

[82] ARTICLE X

Use of the preceding observations to discover the transparency of a certain *thickness of air*

WE MAY REGARD it as one of the principal uses of these last observations to put us in a position to obtain a rather detailed knowledge of the transparency of the air. Mr. de Mairan had already made the ingenious remark, in the Memoirs of the Royal Academy of Sciences for 1721,[77] that supposing one could measure the ratio between the intensities of the light of a heavenly body at two different elevations it would not be impossible to derive from this the transparency or opacity of the atmosphere. This learned academician did not indicate any means of measuring light. He even doubted that the thing was possible.[78] It was also necessary to discover the true law followed by

- Pierre Bouguer (1698 - 1758), Optical Treatise on the Gradation of Light (published posthumously in French in 1860, translated by W.E.K. Middleton, 1961)
- Johann Heinrich Lambert (1728 - 1777), Phtometria sive de mensura et gradibus luminis, colorum, et umbrae (Augsburg, 1760) - google books

Computational Assignment!



To calculate Ln[V_o] from MFRSR data acquired at the Pinnacles tower in the Shenendoah mountains.

1. Read in “Ret_676_20200221v0.9.h5” as an hdf file
2. Plot out the voltages for all the channels and observe
3. Separate the data into AM and PM segments
4. Form ordered pairs of {M(θ), Ln[V_o]} for both AM and PM datasets

4.1. calculate the airmass values yourself and confirm they agree with those in the hdf file

5. Plot up the regressions and assess the total optical depth and the calibration value - Ln[V_o]. You should get something like the plot below

5.1. Note that in these regressions you will want to select for a range of airmasses.

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LangleyReportDWLogSROhdf[ThisDir, ThisDir, "Ret_676_20200221v0.9.h5",
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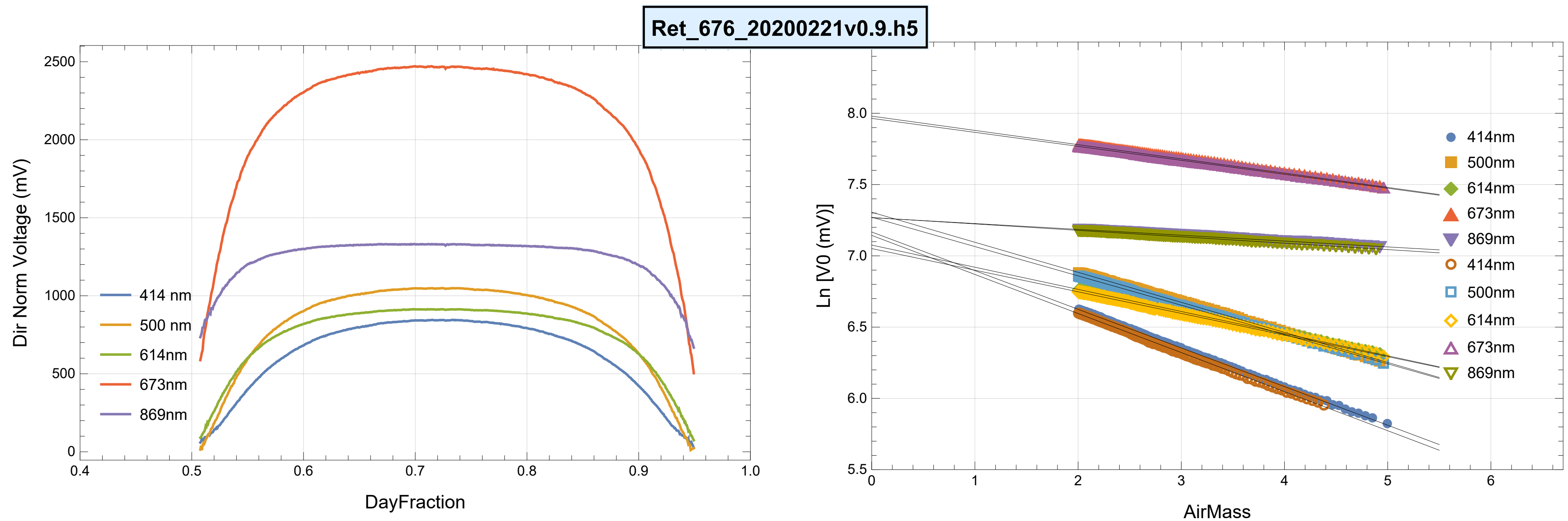

6. Now try your routine on “Ret_676_20200115v0.9.h5”. It will not work too well due to the influence of clouds.

In[∘]:=
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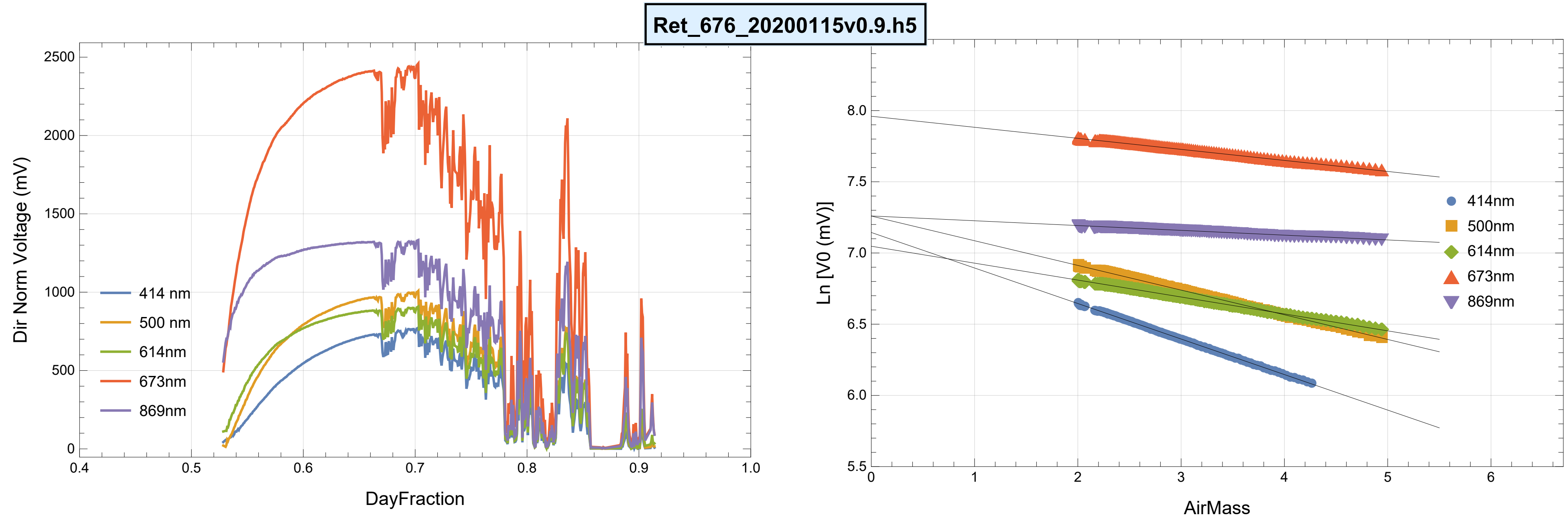

Atmos. Meas. Tech., 9, 215–225, 2016
www.atmos-meas-tech.net/9/215/2016/
doi:10.5194/amt-9-215-2016

Atmospheric Measurement Techniques
Open Access

Non-parametric and least squares Langley plot methods

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[a]formerly at: the Cooperative Institute for Research in Environmental Sciences, University of Colorado, and Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, USA

7. So ... Implement a least squares filter that works as follows (this filter is from:)

7.1. Perform the above linear regression selecting for a particular air mass range.

7.2. Calculate the residuals from the best fit line.

7.3. Discard the one ordered pair that has the largest residual

7.4. Regress the remaining points and repeat.

7.5. Stop the loop when either the RMS of the residuals is less than a certain value (0.006 is suggested in Kiedron et al.) or there are too few points remaining.