Measuring extinction using visibility sensors & modelling approaches based on DNI

Stefan Wilbert, Natalie Hanrieder et al.

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DLR

Content

Extinction measurements with visibility sensors

- Visibility and relation to beam attenuation between heliostat and receiver
- Test of different sensors

Deriving extinction time series from DNI data

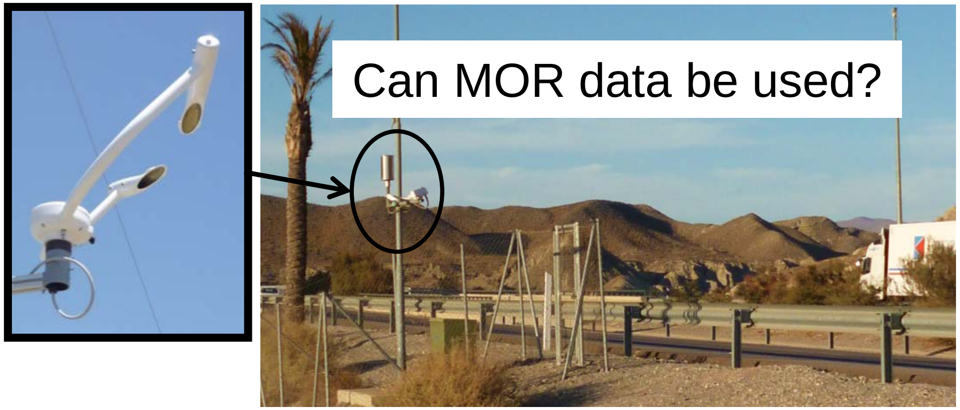
- Idea of the model
- Validation, uncertainty

Extinction and Meteorological Optical Range (MOR)

•**Target parameter for CSP: β_e** from **Beer-law (monochromatic, for all wvlgth)**

$$I(x) = I_0 \exp(-\beta_e x)$$

•Usually, β_e IS NOT measured → Another variable might be used → MOR
-**MOR** is WMO recommended parameter to describe visibility
-MOR is measured for traffic
-roads, airports
-Question from 2009:
Can MOR be used to derive β_e?

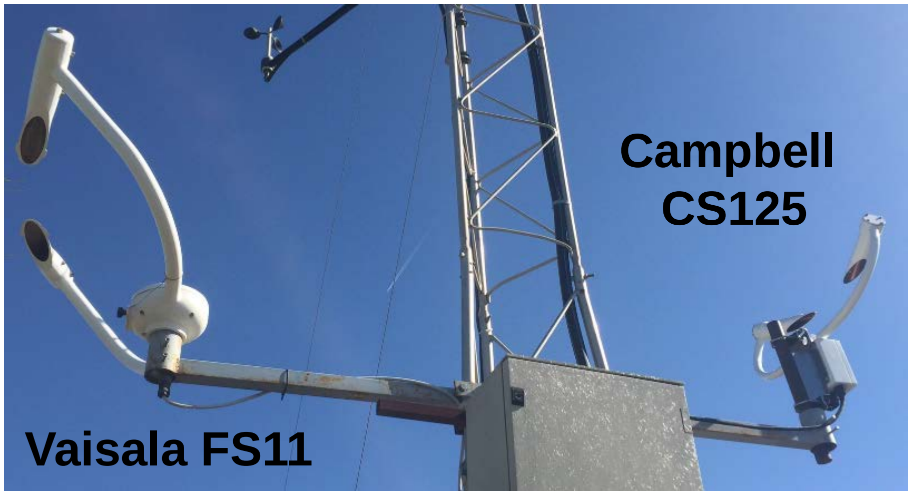


•**Def.:** MOR = Path after which a luminous flux from an incandescent lamp @ color temperature of 2700 K, is reduced to 5% of its original value (WMO, CIMO Guide).

$$MOR \approx -\ln 0.05 / \beta_e$$

Evaluated MOR instruments

-2 transmissometers & 3 scatterometers
-co-located measurements and data comparison



Campbell CS120

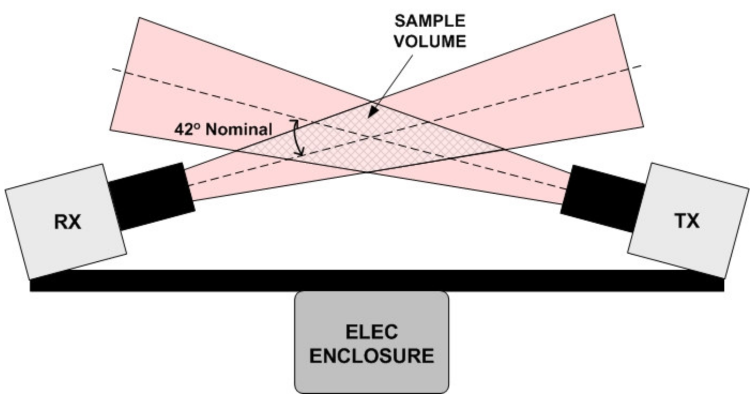
Degreane TR30

Optec LPV- 4

Vaisala FS11 scatterometer

- NIR light beam through volume of air
  → measures forward scattering of pulsed beam

- MOR range: 5m - 75km
  -Corresponds to max. measureable transmittance for 1km light path of $T_{1km} = 0.961$



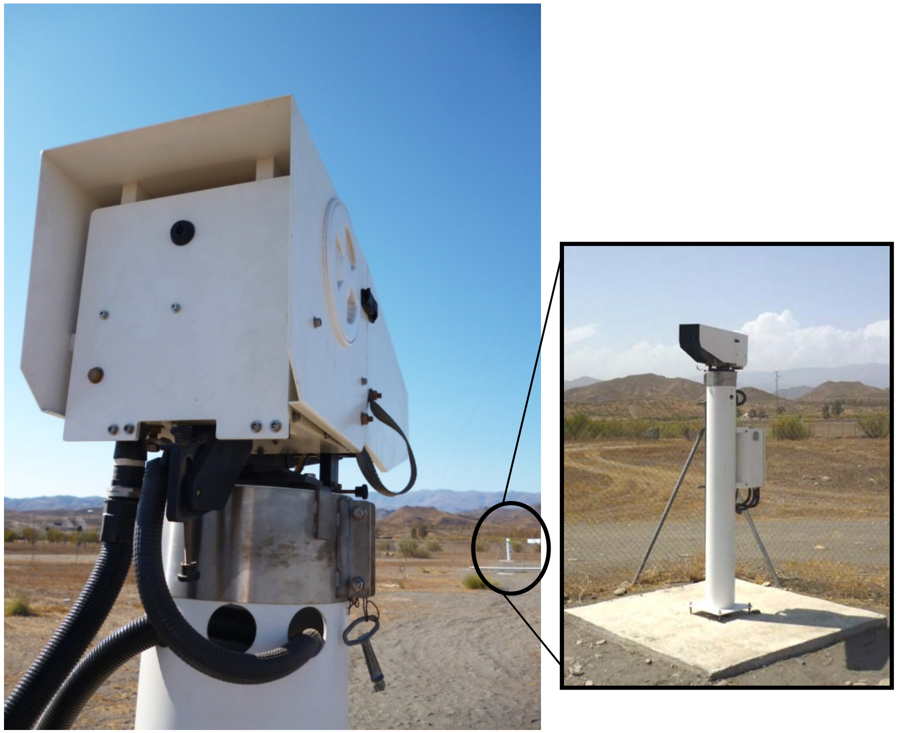
Campbell Scientific scatterometer CS 125

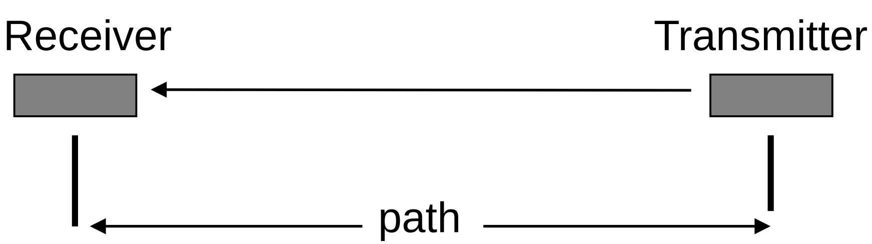
- Principle of operation as FS11
- ⅓ of FS11 price
- MOR range: 5m - 75km
  - Corresponds to max. measureable transmittance for 1km light path of $T_{1km} = 0.961$
- Center wavelength 850 nm
- Also tested newer CS120 (similar to CS125, 1/4 of FS11 price)

Optec LPV-4 Transmissometer

- measures transmittance of pulsed beam
- VIS light beam λ= 532nm
- Path length: up to 20km (selected 487m)
- MOR range: 0.5km - 300km
  - Corresponds to a maximum measureable transmittance for 1km light path of 0.99

Degreane TR30 Transmissometer





- measures transmittance of pulsed beam
- White light beam
  λ= 400 - 700 nm
- path length: 75 m
- MOR range: 5 m to 70 km
  - -Corresponds to a maximum measureable transmittance for 1km light path of 0.958

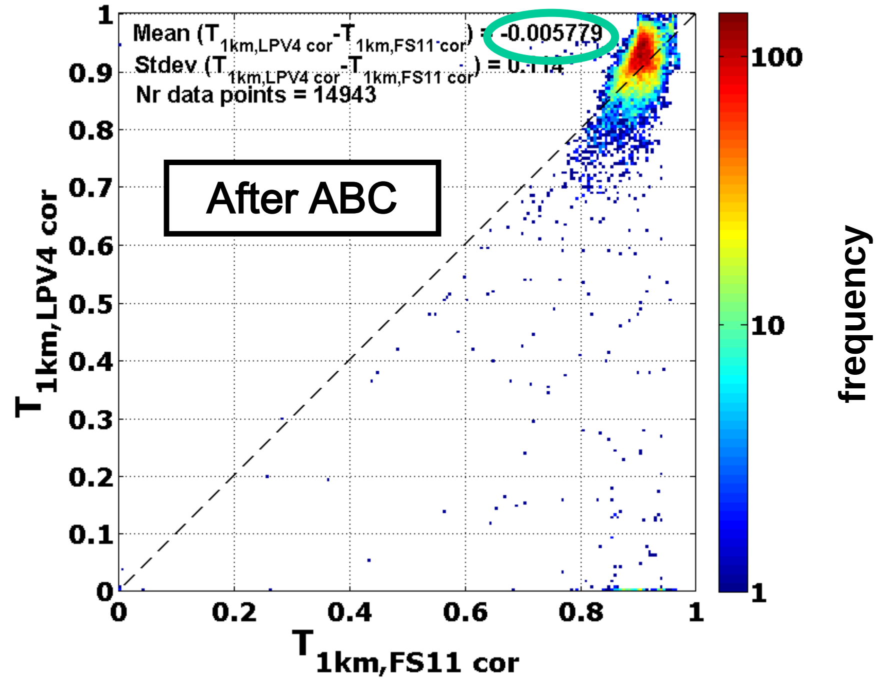
- Conclusion
  - **Instrument not reliable for relevant high MOR range (already visible from measurement data)!**

Validation of FS11 and LPV4

Vaisala FS11

Optec LPV-4

ABC- Absorption and Broadband Correction



- 1 year processed data in 10 min time resolution
- Deviation between sensors noticeable and understandable
  - Spectral measurements (532nm vs. NIR) although broadband target value
  - Variation of absorption not measured by FS11
- No bias after physical correction “ABC”
- FS11 and LPV4 are applicable for CSP!

ABC- Absorption and Broadband Correction

libRadtran

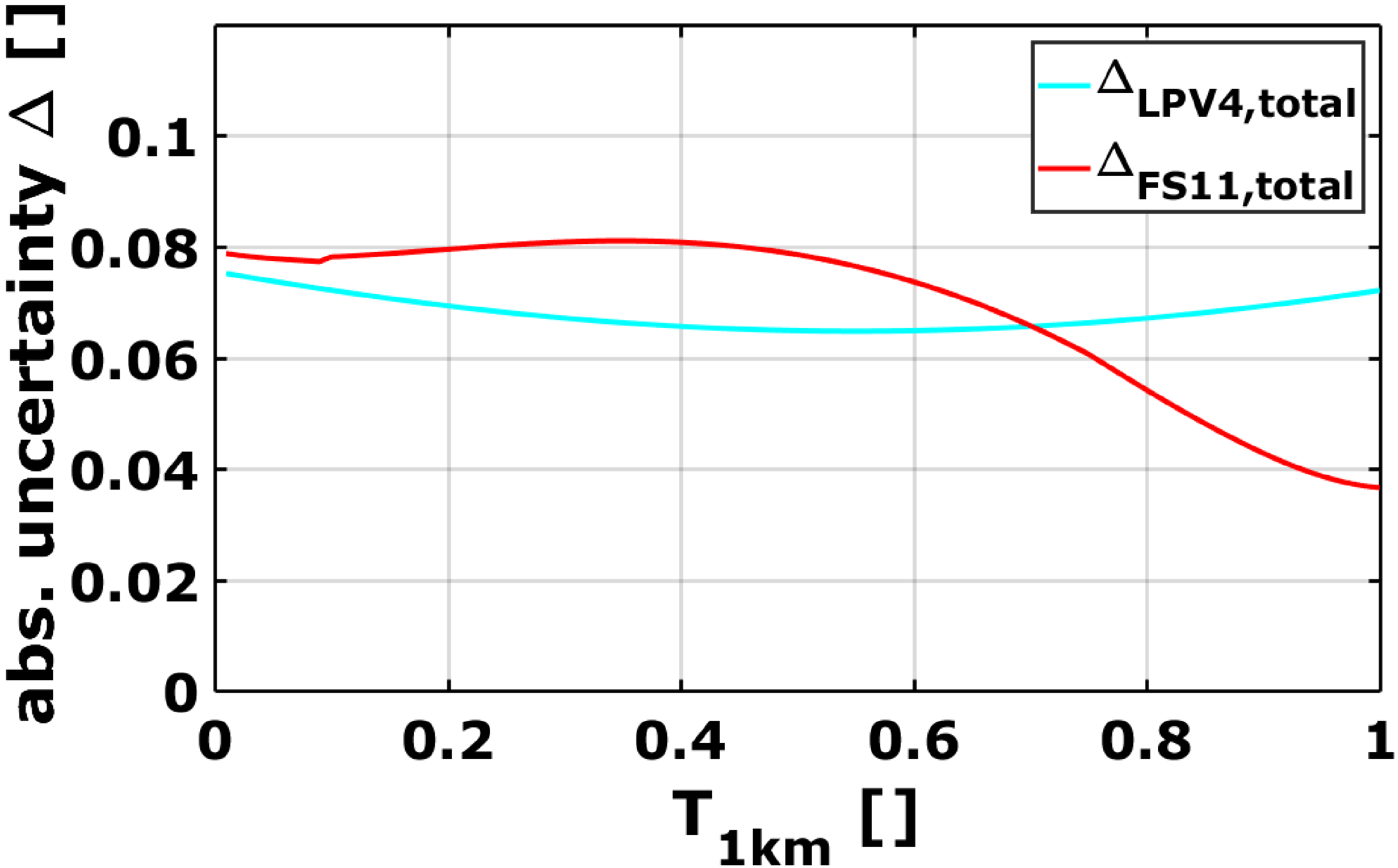
1. Simulate spectral DNI at ground level with libRadtran
   - Use T, rel. hum., press. and AERONET data if available.

2. Simulate spectral DNI after passing through a layer of air with homogeneous properties representing air between heliostat and receiver

3. Calculate absorption and scatter effect for each wavelength

→ Spectral correction factor of signal of the LPV4
  → 532nm -> broadband 280-4000nm
→ Spectral & absorption correction factor of FS11
  → NIR -> broadband
  → deviation from average absorption

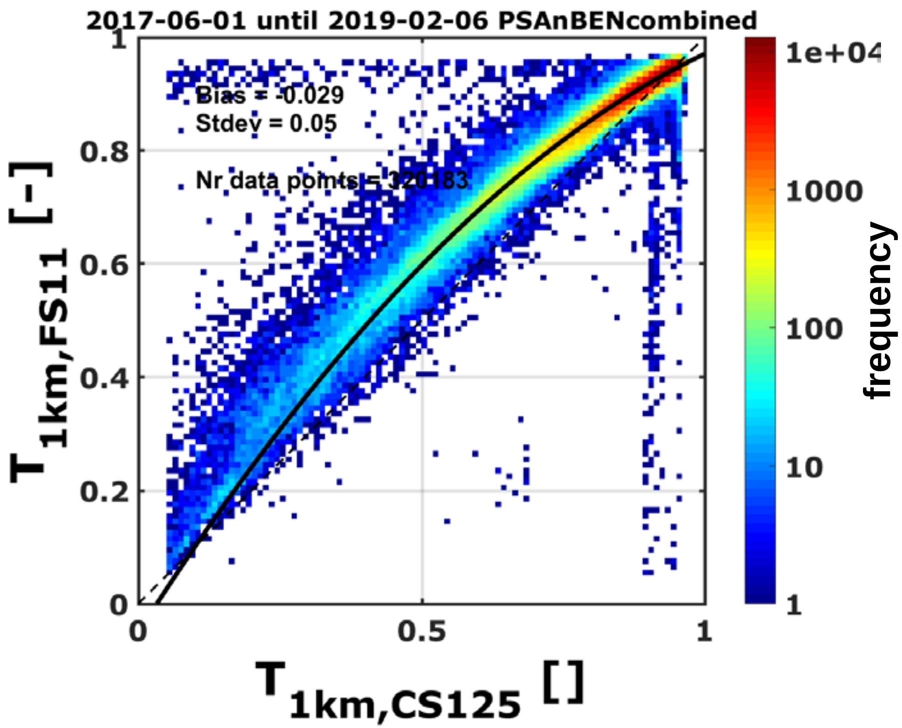
Uncertainty of FS11 and LPV4 based T_{1km} measurement

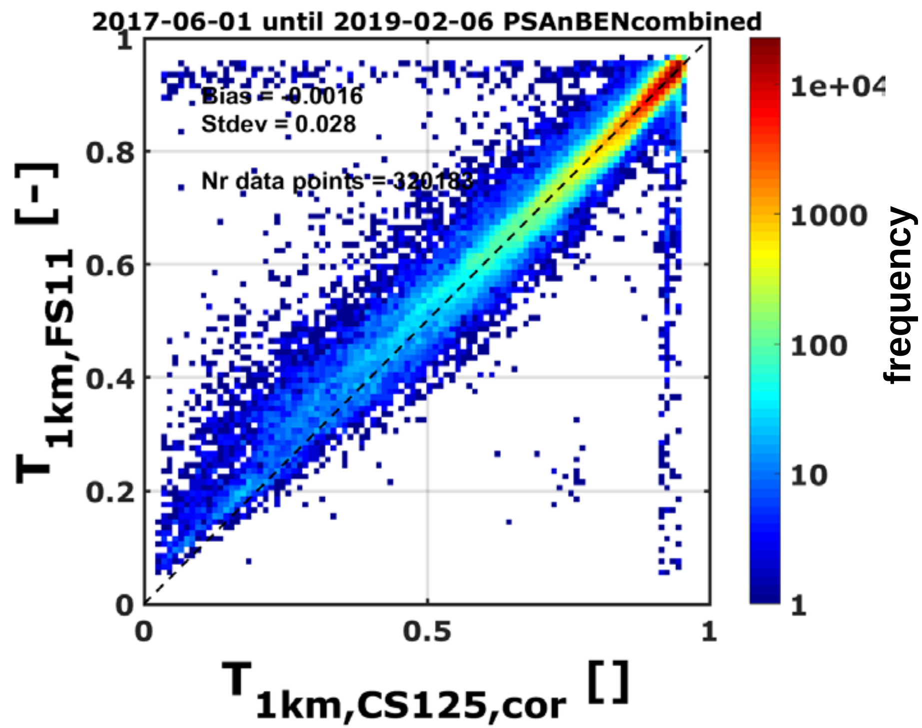


- Significant reduction for LPV4 possible when used with longer distance (e.g. 2km)

Adaptations for different MOR sensors

- Comparison of CS125 and FS11 at CIEMAT's PSA and IRESEN's GEP
- Systematic deviations that can be corrected well
- Similar results for CS120





Further comments on extinction measurement

- Assumption that measurement at the ground represents slant range from heliostat to receiver:
  - Tested at PSA with FS11 and particle counters on ground and at 90m height.
    -> At PSA no deviation due to height
  - During high DNI well mixed atmosphere in the boundary layer is expected
  - LPV4 can be used along slant path

- Many MOR sensors only have measurement range up to ~20km (T_{1km} = 0.86):
  - If working with such data statistical methods or models must be used to derive data for high MORs

Conclusion
Extinction measurements with MOR sensors

- MOR measurements can be used to derive extinction data **if**:
  - adequate sensors are used (e.g. **real** measurement range)
  - ABC correction is applied
- Uncertainty of MOR based ABC corrected extinction data is known.
  - Allows selection of instrument and setup for individual application

- LPV4 is accurate option if daily cleaning and alignment control is possible
- Scatterometers are also interesting if maintenance & robustness are an issue

- Using existing visibility data from sensors already deployed close to a CSP site of interest (road, airports, …) can be a big advantage:
  - Sensors should be characterized by comparison to known MOR sensors or extinction measurement systems (can be done using a sensor of the same model)

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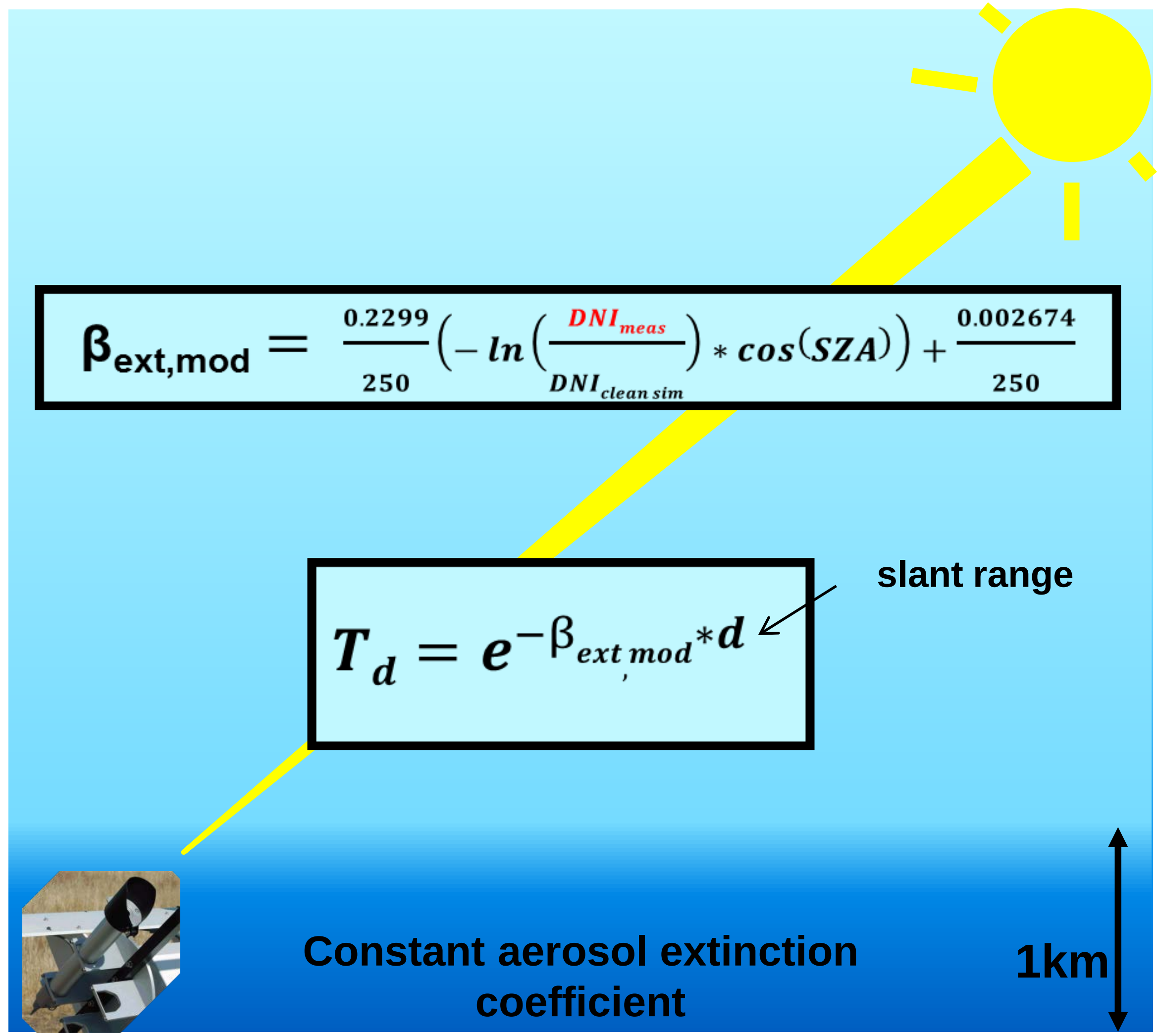
Extinction model based on DNI

Compare clear sky DNI measurement
to
clear sky DNI for one fixed atmosphere without aerosol

=> Estimate of AOD

Assume that aerosol height profile is known

=>extinction coefficient close to ground

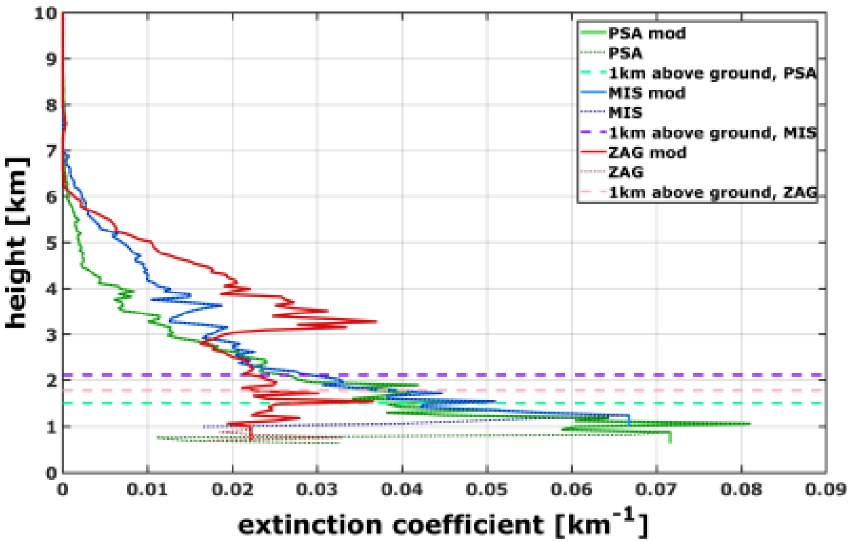


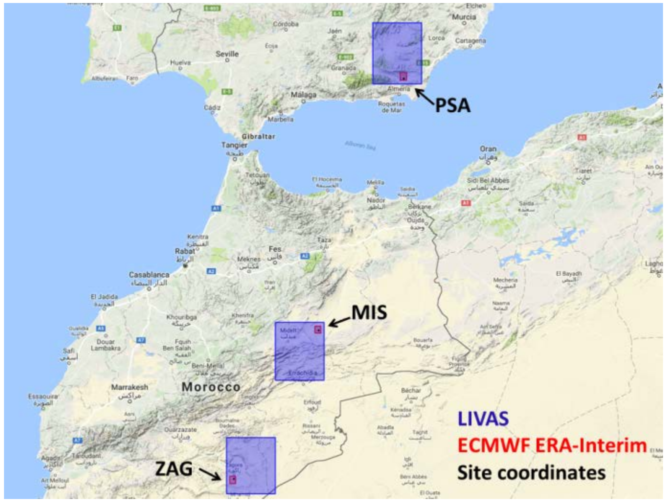
First version by NREL
Sengupta et al., 2011: “Impact of aerosols on atmospheric attenuation loss in central receiver systems”

Enhancements of transmittance model

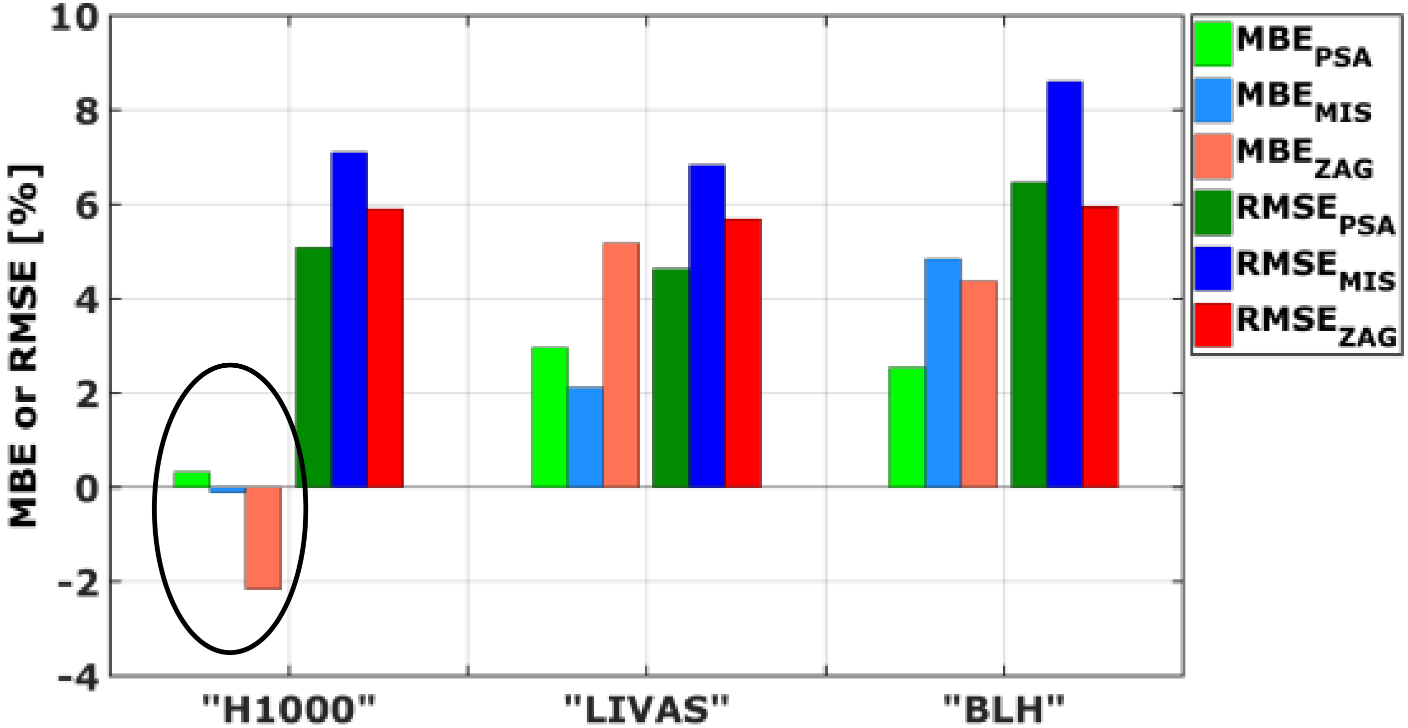
- Consider site altitude
- Consider water vapor content as time series derived from rel. hum. temp. & press.
- Select aerosol type for site of interest
- Vary aerosol height distribution
  - LIVAS LIDAR data
  - Standard libRadtran aerosol profiles
  - Homogeneous extinction up to
    - 1km
    - Ceilometer lowest aerosol layer
    - Boundary layer height data from numerical weather prediction model ECMWF

=> Validation at three sites with several years against FS11 data





Validation of transmittance model in terms of T1km



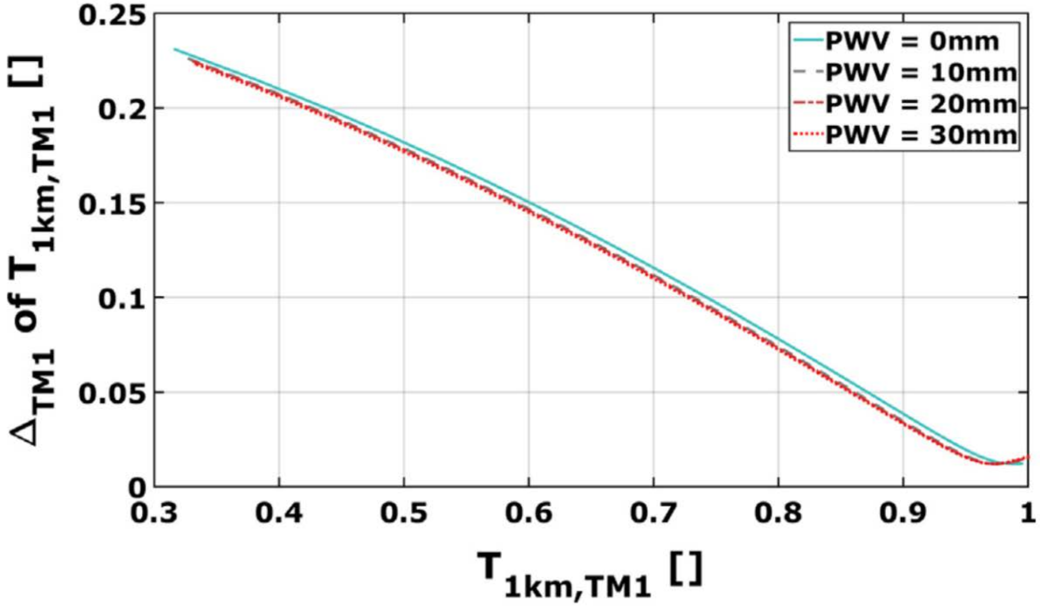
- Avg. transmittances T_{1km} at the three sites:
  -PSA: 89%, MIS: 87%, ZAG 86%
- No advantage for complex evaluations with LIVAS or ECMWF BLH (same for ceilometer aerosol layer & libRadtran standard aerosol profiles)
- Considering uncertainties of the aerosol height profile, errors for „H1000“ are low.

Model uncertainty and possible applications

- Uncertainty of aerosol height profile assumption is biggest influence for uncertainty of T_{1km}
  - Height estimate of homogeneous layer wrong by factor X => extinction coefficient wrong by 1/X.
  - However, low influence for high T_{1km}
    - A multiple of a low extinction coefficient is still low.

=> Model can identify clear sites and to indicate of a measurement is needed!

-If low transmittance is found measurement campaign is required.



Conclusions – DNI based transmittance model

- DNI based modelling of transmittance is possible
- T_{1km} errors for 3 validation sites are within ~2% (bias)
  - Simple assumption of homogeneous 1km layer from NREL's original model performed best

- Model can identify clear sites with high transmittance
  - Model data only accurate for CSP plant simulation for high transmittance values
  - Lower model transmittances are estimates and indicate that a measurement campaign is required.

Thank you for your attention!

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Selected references

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