An alternative zenith-sky ozone retrieval algorithm for the Brewer spectrophotometer

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Introduction

The Brewer spectrophotometer (Fig. 1) estimates the total ozone content (TOC) in the atmosphere from measurements of ultraviolet solar radiation in two different observation modes:

- In the **direct sun** (DS) geometry, the Brewer directly points to the sun;
- In the **zenith sky** (ZS) geometry, the Brewer points to the zenith and records polarised, scattered radiation.

ZS observations are very useful when the sun is low on the horizon (e.g., at **high latitudes**) or when the sun is not directly visible (e.g., at **mountain valley sites** in wintertime). Moreover, ZS estimates are considered to be less affected by the presence of **clouds**, thus allowing to generate long-term ozone time series unbiased by meteorological conditions.

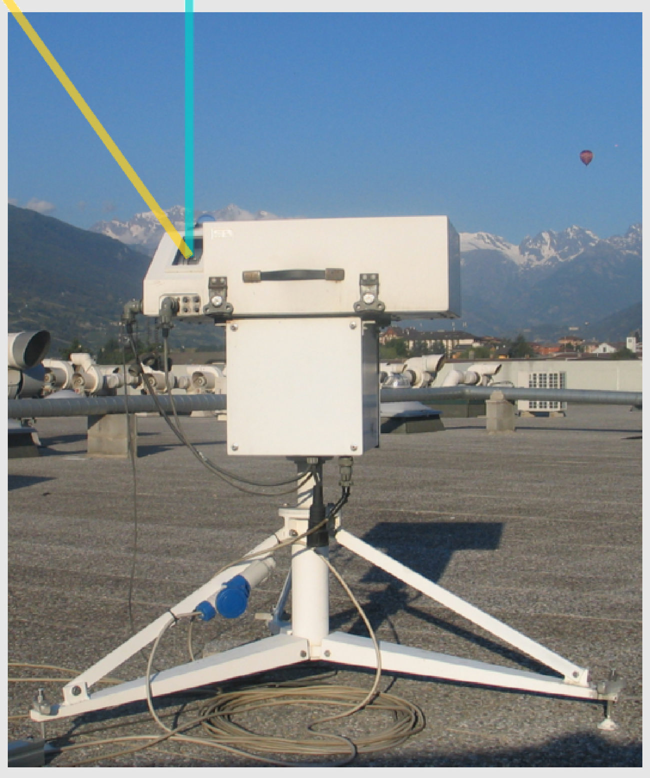

Fig.1 Brewer spectrophotometer #066 at Aosta, Italy.

The standard algorithm: zenith sky charts

The first algorithm to retrieve ozone from zenith measurements was developed by Dobson (1957) and is based on the so-called "zenith sky charts", i.e. **empirical functions** describing the relation between the zenith radiance and the ozone content. Such polynomials are determined through **comparison between DS and ZS** observations. Fioletov et al. (2011) integrated this method with radiative transfer calculations.

The zenith sky charts **only hold locally** (at a small range of mu and ozone), e.g. the polynomial is not proportional to the ozone absorption or the air mass factor (AMF) making not possible even theoretically to behave at AMF=0 or TOC=0.

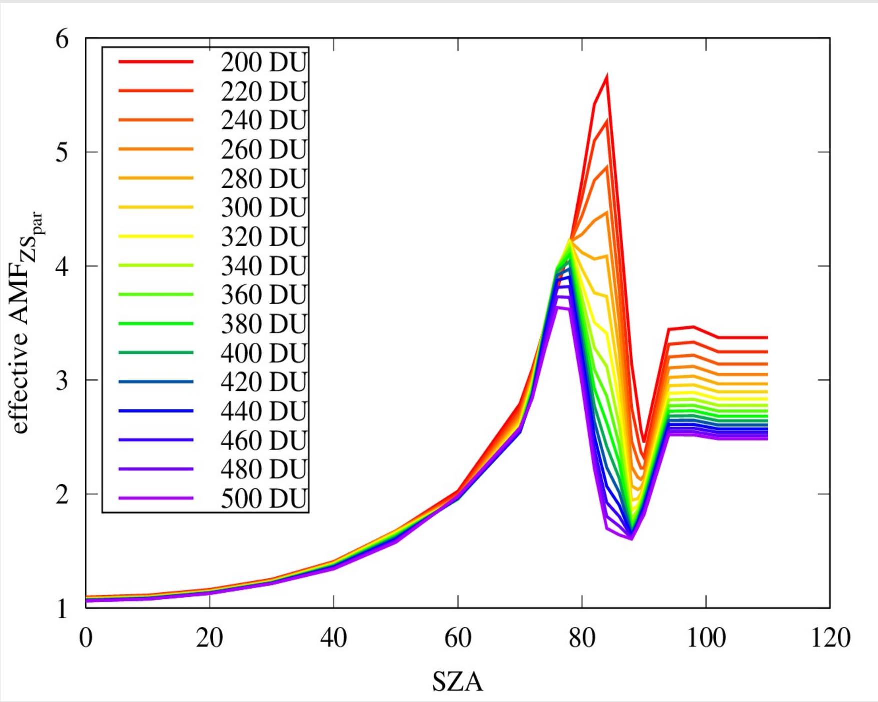

Fig. 2
Effective AMF for ZS measurements calculated with the SCIATRAN model as a function of the solar zenith angle and the TOC.

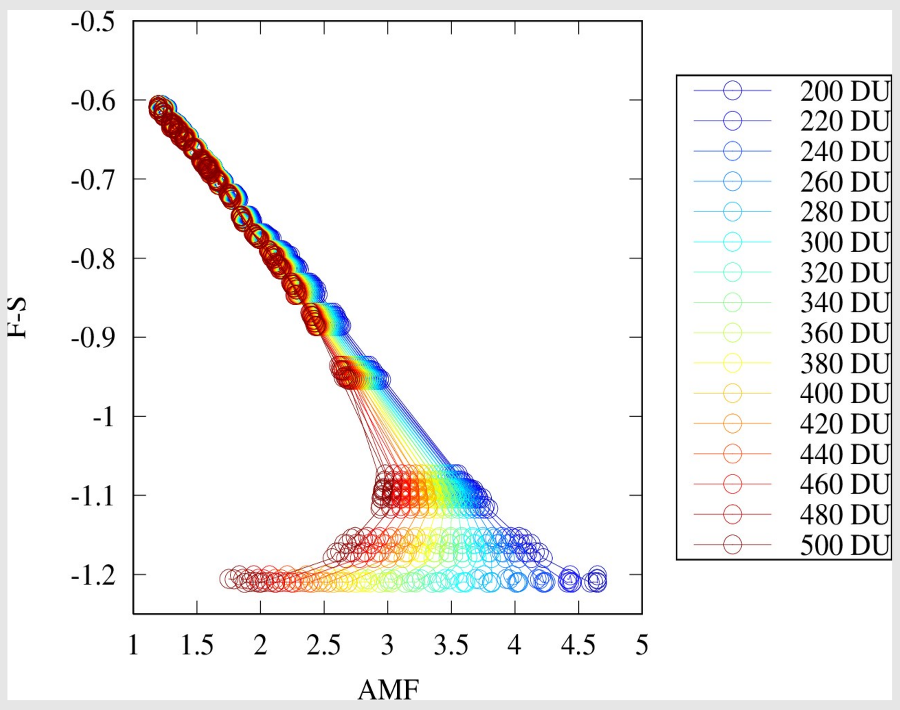

Fig. 3
Example of a zenith-sky Langley plot to estimate the instrumental constant. Since the ZS AMF is a function of the TOC, one Langley for each TOC was plotted.

The alternative algorithm: effective air mass concept

In the present work, we propose an alternative method fully relying on a **formal description** of the radiative transfer rather than on approximate polynomials and correction factors. The mathematical formulation by Marquard et al. (2000) can be adopted to describe the spectral radiance I(λ) **scattered from the zenith** to the surface as a function of the TOC:

$$I(\lambda, TOC) = I(\lambda,0)\int d\Gamma\, p(\lambda,\Gamma)\, e^{-\int_\Gamma ds\,\sigma(\lambda,s)\,n(s)}$$

The exponential term is the well-known **Bouguer-Lambert-Beer (BLB) law** (σ is the ozone cross section and s the length of the path), weighted by the probability (p) that a photon will follow the path Γ. I(λ,0) is the intensity that would be measured in a purely-scattering atmosphere.

Extinction of **direct** sunlight is described by the **much simpler** BLB law:

$$I_{DS}(\lambda, TOC) = I_{DS}(\lambda,0)e^{-\int dz\,\mu(\theta)\,\sigma(\lambda,z)\,n(z)}$$

where μ is the AMF. The **introduction of a proper "effective" zenith-sly AMF function**, calculated by a radiative transfer model (SCIATRAN, with full-spherical geometry and polarisation), allows to **use the same formalism for both the zenith and the direct radiation** (e.g., Hendrick et al., 2011; Diémoz et al., 2014)

However, **ozone is a strong absorber** at the Brewer ozone measuring wavelengths (Huggins band), thus the ozone path and the AMF will depend on the TOC (Fig. 2).

Proof-of-concept at Mauna Loa Observatory

Mauna Loa Observatory (MLO, 3400 m asl, 19.536°N, 155.576°W) represents the ideal site to test the retrieval algorithm. A **Langley plot** was first performed to calibrate MkIII Brewer #145. Since the AMF is a function of the (a priori unknown) TOC, the Langley plot must be repeated for several guesses of TOC (Fig. 3), then the "best" curve is chosen (e.g., according to the linear correlation coefficient or comparing the the first guess with the average TOC from the slope of the Langley).

Then, **ozone is estimated from instantaneous measurements** using the extraterrestrial constant. Again, since the AMF depends on the TOC, an **iterative procedure** was adopted. The mean deviation between ZS and DS estimates is **-0.11 DU** with a root-mean-square error of **2.7 DU** (i.e., ~1%, Fig. 4).

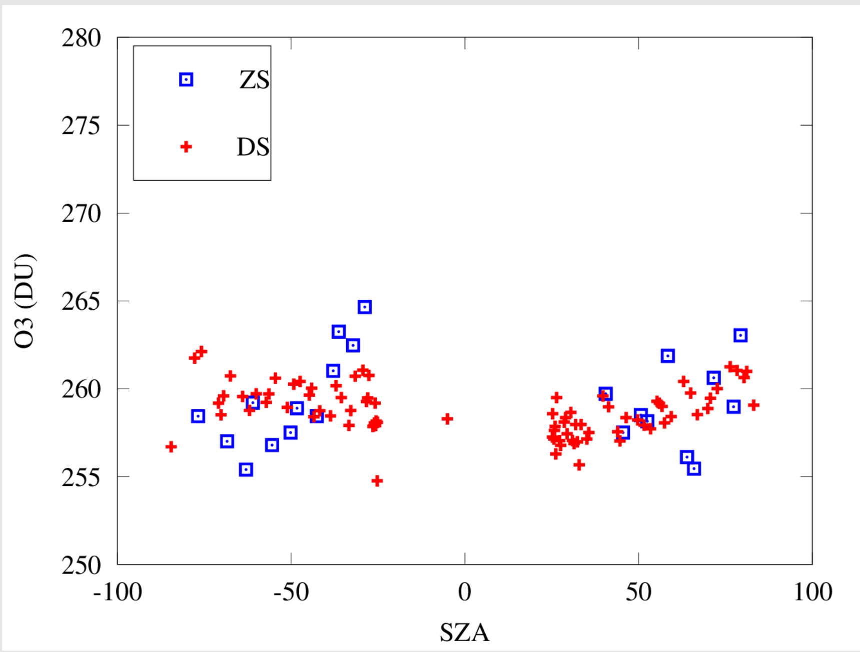

Fig. 4
Ozone retrieved at MLO on October, 12th 2015 as a function of the solar zenith angle (negative angles = morning, positive = afternoon).

Conclusions and further research

- The alternative technique is fully able to **separate instrumental and atmospheric effects**;
- The technique is **completely independent from DS**, thus allowing consistent DS/ZS comparisons;
- A **method to auto-calibrate** the instrument at pristine sites is provided;
- The alternative formulation permits the use of **different climatological ozone profiles** (e.g., monthly profiles) **with the same ETC**, without the need of readjusting any polimonial.

Further research is planned to:

- Analyse long-term zenith sky datasets at **different locations**;
- Test measurements at **different polarisation planes** and in **cloudy conditions**;
- Measure ozone at **longer wavelengths** to avoid strong absorption and reduce noise;
- Study the sensitivity to **ozone partitioning** between the troposphere and the stratosphere.

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