Satellite retrieval of aerosol absorption over the oceans using sunglint

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[1] Aerosol absorption of sunlight, in particular by black carbon - soot and dark organic material produced from incomplete combustion of fossil fuel and from vegetation fires, is emerging as a key component of climate forcing. However, global characterization of black carbon emissions, distribution and absorption of sunlight cannot be determined within a factor of 5. Here we propose that the oceanic sunglint can be used as a bright background against which aerosol absorption can be measured from space. The method can map global ocean glint every 4–10 days and determine the distribution of aerosol absorption optical thickness with an error of ±25% for aerosol optical thickness of 0.2 to 0.4. 18 % of the ocean observations are for this range of optical thicknesses. The monthly average aerosol absorption is estimated to have an error of ±12% and uncertainty in the single scattering albedo of ±0.02. We outline a satellite design to perform the measurements. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305). **Citation:** Kaufman, Y. J., J. V. Martins, L. A. Remer, M. R. Schoeberl, and M. A. Yamasoe, Satellite retrieval of aerosol absorption over the oceans using sunglint, *Geophys. Res. Lett.*, *29*(19), 1928, doi:10.1029/2002GL015403, 2002.

1. Introduction

[2] Carbonaceous aerosol contains soot and dark organic material from incomplete combustion in vegetation fires and fossil fuel engines. We will refer to this material by the generic name - black carbon (BC). In contrast to aerosol solar scattering that reduces global warming, BC absorption of sunlight increases global warming. BC global radiative forcing has been estimated to be 0.5–0.8 W/m^2 [*Haywood and Boucher*, 2000; *Jacobson*, 2001], or up to a third of greenhouse warming.

[3] Large concentrations of BC are found in regions with tropical biomass burning [*Eck et al.*, 2001] and pollution over East and South Asia. Over the Indian Ocean BC was shown to absorb on average 7% of sunlight reaching the surface, or 17 W/m^2 [*Ramanathan et al*, 2001a]. Such reduction of solar energy absorbed by the surface is expected to slow down the hydrological cycle [*Ramanathan et al*, 2001b] and reduce cloud formation [*Ackerman et al*, 2000]. BC from East Asia can be transported long distances from the source [*Clarke and Charlson*, 1985].

[4] Current estimates of BC concentration and absorption are uncertain due to uncertainties in the source estimates (factor of 2), life-time in the atmosphere (factor of 2) and BC light absorption efficiency (factor of 3–4) [*Tegen et al.*, 2000; *Martins et al.*, 1998]. In the last 40 years its industrial/urban sources probably have tripled [*Tegen et al.*, 2000]. Similar increases may be expected in the next decades due to the expansion of economic activity in East and South Asia.

[5] Systematic, global measurements of BC absorption are needed to estimate its impact on the climate system. To measure aerosol absorption from space, the dark aerosol has to be viewed against bright surface. Satellites have been used to measure aerosol absorption over a bright desert near the seashore [*Kaufman et al.*, 2001a]. Absorbing aerosols are also measured by UV space instruments (TOMS, GOME), however analyis of the UV data is less sensitive to aerosol close to the surface and suffers from cloud contamination in the present satellite resolution of 50–90 kms [*Torres et al.*, 2002].

[6] Here we suggest a new method to estimate BC absorption. This method, not available from present satellites, uses measurements of the spectral attenuation of ocean sun glint reflectance to derive the distribution of aerosol absorption over the oceans. The method resembles water vapor measurements using the glint [*Kleidman et al.*, 2000]. Since oceans cover about two thirds of the globe this method would significantly increase our ability to provide a global assessment of the role of aerosol absorption and BC in climate.

2. Ocean Glint and Aerosol Absorption

[7] Glint brightness varies mostly in response to changes in the sea surface roughness, and cannot be estimated with the required accuracy (~1%) to evaluate the aerosol attenuation, however the spectral properties of the glint are well known [*Cox and Munk*, 1954]. Thus, in order to account for the glint reflection at least one spectral channel with no or low aerosol absorption is needed.

[8] The glint technique to measure aerosol absorption is applied to dust and to fine smoke or pollution aerosols. Dust absorption in the near-IR is around zero [*Kaufman et al.*, 2001a]. Therefore satellite measurements of the glint at 0.86 μm are not influenced by dust absorption and can be used to derive dust absorption in shorter wavelengths. Smoke or pollution aerosols are dominated by fine particles with AOT that decreases steeply with wavelength. Aerosol absorption is 3 to 6 times smaller at 2.13 μm than at 0.4–0.6 μm [*Dubovik et al.*, 2002]. Therefore the 2.13 μm is the best wavelength to detect the glint reflectance in the presence of smoke or pollution aerosols.

[9] Figure 1 shows a simulation of the aerosol effect on glint observations from space for wind speed of 7 m/s.

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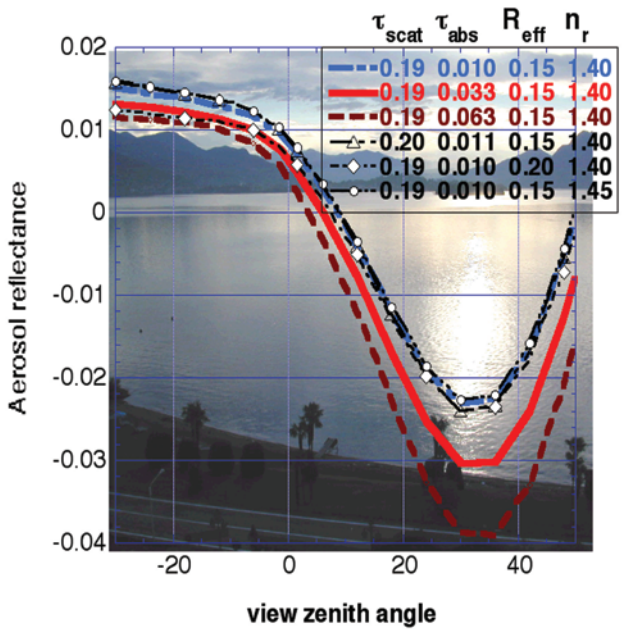

Figure 1. Solar glint in Lago Maggiore, Italy on a pristine day (June 14, 2001) overlaid by a plot of the calculated aerosol reflectance - top of atmosphere reflectance difference with and without aerosols at 0.55 μm. Solar zenith angle is 30°. Blue, red and orange lines are for increasing aerosol absorption optical thickness, τ_{abs} for the same τ_{scat}. Black lines are for varying optical thickness, effective radius, R_{eff} and refractive index n_r. The aerosol reflectance in the glint is robust against such changes in most aerosol properties but sensitive to its absorption.

The aerosol reflectance is defined as the difference between the reflectance of the ocean/atmosphere system with and without aerosols. Outside the glint, aerosol increases the ocean brightness observed at the top of the atmosphere. In the glint region, aerosol reduces the glint brightness both through absorption and scattering of reflected sunlight.

[10] The aerosol reflectance is sensitive to aerosol absorption in the glint while at off glint angles it is sensitive to aerosol size distribution and real part of refractive index. A change in the effective radius, $\Delta r_{eff} = 0.05$ μm or a change in the refractive index, $\Delta n_r = 0.05$, affects the aerosol reflectance outside the glint, as much as a change in the aerosol absorption optical thickness, $\Delta\tau_{abs} = 0.03$ (see Figure 1). However, the aerosol reflectance inside the glint is not sensitive to aerosol size or refractive index in this case. This insensitivity is due to the compensation between a change in the attenuation of the glint brightness and a change in aerosol backscattering of sunlight to space. This compensation may not take place for much different wind speeds or aerosol size distributions.

3. The Remote Sensing Method

[11] Aerosol reflectance in the glint is affected both by aerosol scattering and absorption. Aerosol scattering is determined first from off glint measurements in the same location. The technique is illustrated in Figure 2. The figure shows two cross track scanning multi-wavelength polarimeters [*Mishchenko and Travis*, 1997]), called here POL_1 and POL_2. Polarization measurements from space are shown to provide accurate aerosol scattering optical properties when a wide range of view directions is available [*Chowdhary et al.*, 2002]. In the Figure 2 configuration, POL_1 points always to the center of the glint and scans through it, POL_2 scans at 40° from the glint to see the same spot a minute apart at an off-glint direction. Aerosol properties are derived in the following method:

1. *Aerosol scattering properties*: In the off-glint direction, POL_2 observes aerosols against the dark ocean using polarization measurements in a wide spectral range (0.34–2.1 μm). This information is used to derive the aerosol scattering optical thickness, size distribution (distinguishing dust from fine aerosol) and refractive index.

2. *Glint reflectance*: Glint spectral measurements at 1.6 and 2.1 μm are used to derive the glint reflectance in a spectral region where fine mode aerosols are transparent (see Figure 3). A model, validated using satellite measurements in regions with very little aerosol, can be used to relate the glint brightness in 1.6 or 2.1 μm to the 0.44–0.66 μm range. Thus we can remove the effect of sea surface state on the variation in glint brightness. For dust, a similar procedure is applied using 0.86 μm since dust, does not absorb in this wavelength.

3. *Aerosol absorption*: The excess attenuation of the glint by fine aerosol in the 0.44–0.66 μm range relative to 1.65 or 2.13 μm and the aerosol scattering properties derived from off-glint, are used to derive the aerosol

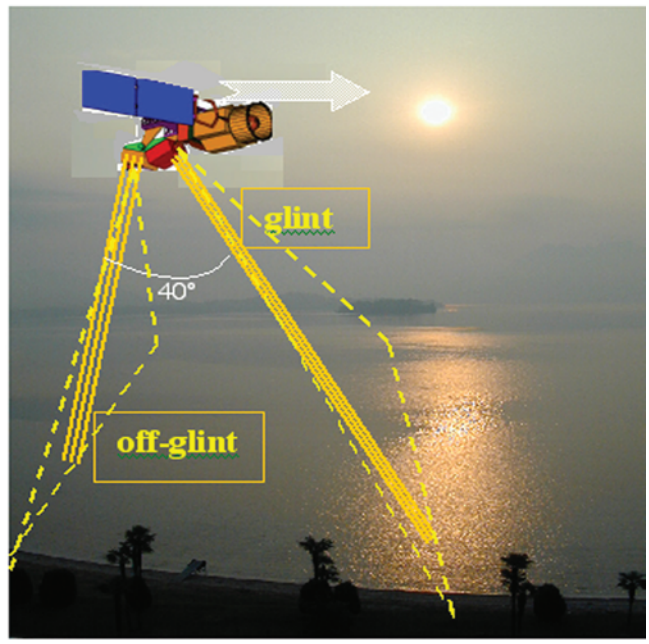

Figure 2. Solar glint over Lago Maggiore, Italy, June 27, 2001. The haze is urban pollution (optical thickness ~1) plus dust from the Sahara [*Gobbi et al.*, 2000]. A hypothetical spaceborne mission to measure aerosol absorption over the ocean consists of two pushbroom instruments that scan across-track as the spacecraft moves along track: one through the glint and one 40° off-glint.

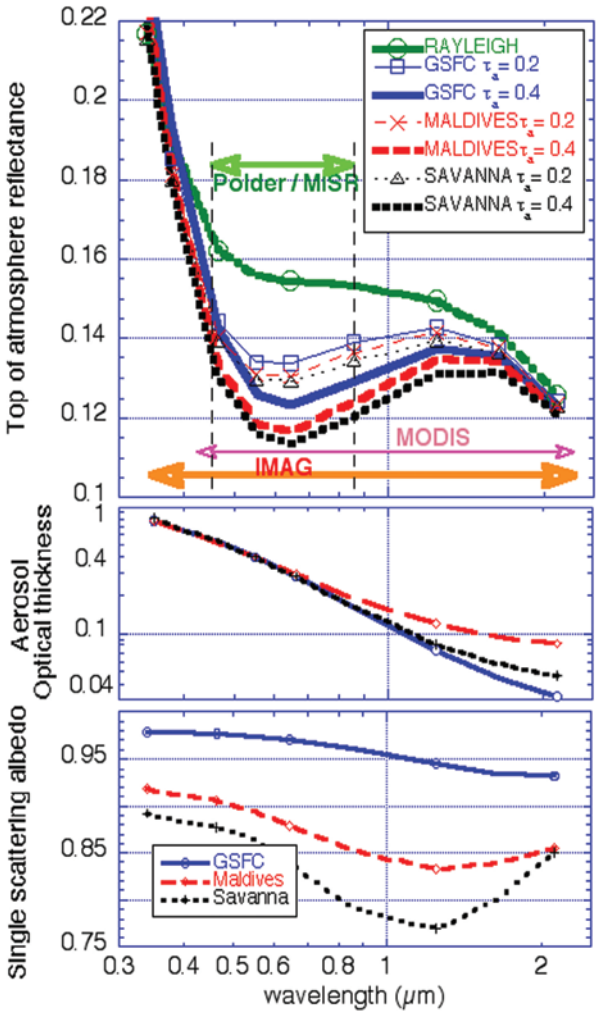

Figure 3. Top of atmosphere reflectance with and without (green line) aerosol, over the glint for wind speed of 7 m/s. Blue, red and black lines are three aerosol types: regional US pollution in GSFC-Maryland, South- Asia pollution in Maldives Island during the INDOEX experiment, and Savanna burning in Africa during the SAFARI-2000 experiment, respectively. The spectral optical thickness and the single scattering albedo for each aerosol type are plotted in the lower figures. The aerosol model is after *Dubovik et al.* [2002].

spectral absorption of sunlight using a radiative transfer lookup table.

4. *Aerosol absorption in the UV*: Using the UV channels at 0.34 and 0.38 μm we can also derive a measurement of the aerosol scattering and absorption optical thickness [*Torres et al.*, 2002] simultaneously.

[12] Figures 3 illustrates the method to derive absorption for three types of fine mode aerosol with different single scattering albedo, ω_o. The higher the optical thickness, or the lower the single scattering albedo, the larger is the aerosol effect on reduction of the glint reflectance. At 1.65 to 2.1 μm the aerosol effect on the glint reflectance is small. However there are no measurements of ω_o in these wavelengths, and the values in Figure 3 are estimated using aerosol measurements in shorter wavelengths. Aerosol absorption is derived from the absorption function A:

$$\mathbf{A}(\tau_a, \omega_0, \lambda) = [\rho'(\tau_a, \omega_0, \lambda) - \rho'(\tau_a = 0, \lambda)] - [\rho'(\tau_a, \omega_0, 2.1) - \rho'(\tau_a = 0, 2.1)]$$

where $\rho'(\tau_a,\omega_0, \lambda)$ is the spectral reflectance of the glint as observed from space for wavelength λ and optical thickness τ_a at 0.55 μm, and single scattering albedo ω_0. $\rho'(\tau_a = 0, \lambda)$ is the value with no aerosol derived from the measured reflectance at 2.1 μm.

[13] A lookup table of **A** for variety of aerosol scattering properties, optical thickness and values of the spectral single scattering albedo can be used to derive the aerosol absorption. An assumed relationship between the aerosol absorption at 2.1 μm and that at the shorter wavelengths based on aerosol climatology [*Dubovik et al.*, 2002], can be used, but will have to be refined with actual aerosol absorption measurements for 1.65 and 2.1 μm channels. An example of the relationship between the absorption function **A** and the aerosol single scattering albedo is given in Figure 4 for fine aerosol particles. Sensitivity to the assumed ω_0 at 2.1 μm and to the aerosol size and refractive index is also shown.

4. Sensitivity Study

[14] The sensitivity of the derived aerosol absorption from measurements in the center of the glint to calibration

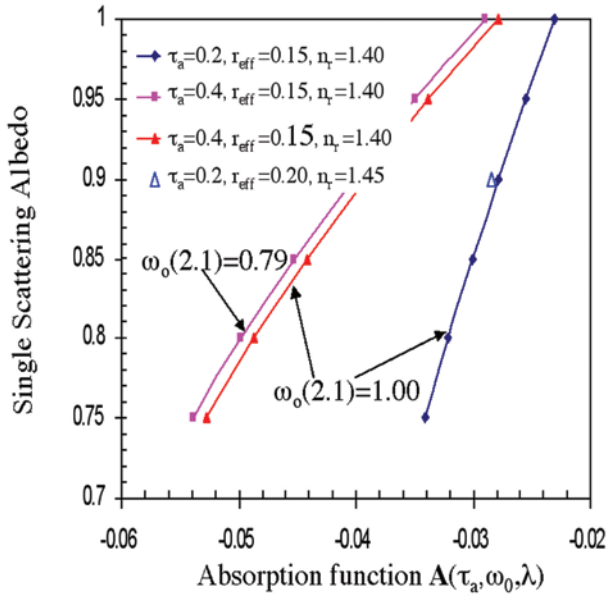

Figure 4. Single scattering albedo, ω_0 at 0.55 μm as a function of the absorption function **A** for fine mode aerosols with optical thickness of 0.2 and 0.4, effective radius of R_{eff} = 0.15 μm, real refractive index of n_r = 1.40 and ω_0 at 2.1 μm of $\omega_0(2.1)$ = 1.0. The sensitivity to R_{eff} = 0.2, n_r = 1.45 and to $\omega_0(2.1)$ = 0.79, is shown. Single scattering albedo has a strong dependence on the absorption function **A** but also on other aerosol properties. An accurate determination of optical depth, effective radius, and refractive index with the off-glint geometry and polarization can narrow down the uncertainties in the absorption measurement.

Table 1. Percentage Error Estimated for the Derivation of Aerosol Absorption Optical Thickness, due to: Calibration Error, ε_C, of 3% for $\lambda < 2.1$ μm, and 1% at 2.1 μm, Error in Effective Radius $\varepsilon_{R\text{-}eff}$ of $\Delta R_{eff} = \pm 0.05$ μm, in Aerosol Optical Thickness, ε_τ, of $\Delta\tau/\tau = 0.05$, in Real Refractive Index, ε_n, of $\Delta n_r = 0.03$, and in the Aerosol Height, ε_H, of $\Delta H = \pm 1$ km

λ μm	τ_{as}	ε_C from 3% to 1%	$\varepsilon_{R\text{-}eff}$ ΔR_{eff} = 0.05 μm	ε_τ $\Delta\tau/\tau$ = 0.05	ε_n Δn_r = 0.03	ε_H ΔH = ±1 km	RMS single Case	RMS monthly
Aerosol optical thickness of 0.2 (0.55 μm)								
0.34	**0.032**	**20**	**−15**	**2**	**8**	**−17**	**27**	**14**
0.38	**0.028**	**15**	**−3**	**2**	**11**	**−12**	**19**	**9**
0.47	**0.025**	**14**	**13**	**−5**	**14**	**−5**	**23**	**11**
0.55	**0.021**	**23**	**3**	**−23**	**12**	**−2**	**34**	**17**
0.64	0.017	37	−37	−52	8	2	74	33
Aerosol optical thickness of 0.4 (0.55 μm)								
0.34	**0.064**	**10**	**−22**	**0**	**5**	**−14**	**28**	**13**
0.38	**0.056**	**7**	**−19**	**2**	**7**	**−9**	**23**	**11**
0.47	**0.049**	**8**	**−11**	**0**	**10**	**−4**	**16**	**8**
0.55	**0.042**	**12**	**−15**	**−8**	**11**	**−1**	**23**	**11**
0.64	0.034	20	−37	−25	11	1	50	25

errors, errors in the effective radius, refractive index and optical thickness is tested and summarized in Table 1. We assume that half the individual errors remain on a monthly average and are used in the monthly RMS. The sensitivity study in Table 1 shows that the average monthly RMS error in the short wavelengths of 0.34 – 0.55 μm is ∼13% for optical thickness of 0.2 and ∼11% for 0.4. Analysis of MODIS daily data for the year 2001 shows that 18% of the observations are for optical thickness between 0.2 and 0.4. 74% of the observations are for lower optical thicknesses and proportionally higher errors.

[15] The spectral analysis of Table 1 is for the center of the glint. Similar uncertainty in the aerosol properties can be reached over a swath of 550 km corresponding to global coverage in 4 days. The calculations are for solar zenith angle of $\theta_o = 30°$. Similar results are obtained for $\theta_o < 30°$. However for $\theta_o \sim 60°$ the glint region is significantly narrower. Therefore, the best analysis of aerosol absorption can be obtained for $\theta_o < 45°$ corresponding to a 90° latitude wide band varying seasonally with the solar position. The calibration accuracy used in Table 1 can be achieved by continuous intercomparison with AERONET measurements of aerosol absorption over clean oceanic sites (absorption of $\tau_{abs} \sim 0.004$ and a similar uncertainty in the absorption of $\Delta\tau_{abs} \sim 0.004$ [*Smirnov et al.*, 2001]). The error of $\Delta H = \pm 1$ km may be reduced by estimating the aerosol height using UV polarization measurements.

5. Summary and Conclusions

[16] A new measurement strategy for the assessment of absorption by BC aerosol is presented for a hypothetical space mission. This strategy uses near simultaneous spectral polarimetric measurements of the ocean sun glint and off glint regions. It offers the possibility to observe fine aerosol absorption of sunlight over oceans and inland waters with errors of ±25% for individual observations and ±12% monthly average. Using a 550 km wide instrument swath, typical of a pushbroom sensor, that scans across the satellite track, the satellite, flying in polar sun synchronous orbit near 700km could provide global coverage in 4 days.

[17] This accuracy of the aerosol sun-glint measurement has been calculated for moderate wind speeds (∼7m/s) and for low solar zenith angles (e.g.< 45°). The method is not as good for high (≥10m/s) or low (≤3m/s) wind speeds where the glint region is narrower or not as bright. The method presented here would generate a climatology of black carbon absorption with high accuracy corresponding to error in the single scattering albedo of ± 0.02. The method was developed for aerosol dominated by fine particles ($R_{eff} < 0.5$ μm), but can be applied to large particles with some modifications.

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