SCIAMACHY TOA REFLECTANCE CORRECTION EFFECTS ON AEROSOL OPTICAL DEPTH RETRIEVAL

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ABSTRACT

Aerosol retrieval from SCIAMACHY data processing at ISAC-CNR has been carried-out to retrieve Aerosol Optical Depth (AOD) at 500 nm wavelength together with a parameter (class) which defines a set of chemico-physical properties pertaining to suspended particles. SCIAMACHY Level 1B data from nadir measurements both over ocean and land are used as input for this processor. SCIAMACHY, onboard ENVISAT, is a remote sensing spectrometer measuring sunlight scattered, transmitted and reflected by the Earth's surface-atmosphere system. Its wavelength range spans from about 240 nm to about 2440 nm, with a spectral resolution varying from 0.24 nm in the UV to 1.48 nm in the NIR. In this aerosol retrieval algorithm, working wavelengths are selected in the UV-VIS-NIR range characterized by negligible gases absorption, i.e. lower than 1%. At these wavelengths, measured TOA reflectance are corrected taking into account that SCIAMACHY underestimates the reflectance in the UV and VIS range by 10 to 25% and by 10 to 20%, respectively. Once reflectances, presenting values of cloud coverage fraction lower than 0.05, are properly corrected, they are fitted with modelled reflectances. The couple formed by AOD and class that minimizes the merit function represent the retrieved aerosols parameters for the spectrum being analysed. The effect on the aerosol retrieval of the applied reflectance correction factors will be critically discussed and quantified. Then, SCIAMACHY data relative to 2003 and 2004 and in spatio-temporal coincidence with AERONET measurements have been considered.

1 INTRODUCTION

The SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) is hosted on board ESA ENVISAT satellite. This spectrometer measures sunlight scattered, transmitted and reflected by the Earth's surface-atmosphere system. The wavelength range extends from the UV-VIS-NIR: channels 1-6 from 240 to 1750 nm, channel 7 and 8 in the range 1940-2040 nm and 2260-2380 nm, respectively, the spectral resolution varying between 0.24 nm and 1.48 nm. Considering the alternate limb-nadir mode and the 960 km swath in nadir mode of the instrument, the global coverage is obtained in a period of six days. The ground pixel dimension is typically 60 km across track x 30 km along track for the selected latitudes and channels [1].

Due to its wide wavelength range and spectral resolution, SCIAMACHY measurements turn out to be well suited also for the retrieval of atmospheric aerosol optical properties (AOP), selecting parts of the spectrum where trace gases absorption is minimal. Its spatial resolution allows the detection of significant loadings and spatial distribution of aerosols. Information on the AOP can be also useful in the context of atmospheric trace gases columnar estimation as for the NO_2 retrieval to improve the accuracy of the air mass factor calculation [2, 3].

Absolute radiometric accuracy is a key issue for reliable remote sensing of the aerosol contribution to top of the atmosphere's (TOA) signal. Due to the known SCIAMACHY underestimation [4, 5] of the spectral measurements a proper correction of the TOA reflectance is mandatory to obtain reliable aerosol retrieval. Von Hoyningen et al. [5] introduced a set of SCIAMACHY TOA reflectance correction coefficients in the VIS-NIR range derived from spectral comparison to MERIS measurements over ocean. Similarly, Acarreta et al. [6] provided a reflectance correction procedure for SCIAMACHY in the VIS and NIR range giving different sets of coefficients for different analysed scenes (desert, land, ocean). Moreover, Tilstra et al., [7] presented a reflectance correction method applied to SCIAMACHY measurements in the UV range for desert, land and ocean surfaces using radiative transfer calculations.

In order to retrieve AOP over land and ocean, a SCIAMACHY data (Level 1B v5.01 and v5.04) processing is presented in Section 2 making use of wavelengths selected in the UV, VIS and NIR spectral ranges employing correction coefficient derived from [6] and [7]. The TOA reflectance correction procedure is treated in Section 3 along with its effects on the AOD retrieval. To assess the consistency of the whole aerosol retrieval, SCIAMACHY AOD are compared to AERONET AOD (Section 4).

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2 SCIAMACHY DATA PROCESSING FOR AEROSOL RETRIEVAL

A dedicated processor named ASP (Aerosol retrieval from SCIAMACHY data Processing) has been developed to retrieve AOP from SCIAMACHY nadir reflectance. In particular, a pseudo-inversion method, already used to provide aerosol global maps over ocean from GOME data [8, 9], has been adopted and upgraded [10] and [11]. ASP structure is constituted by three main phases.

After nadir measurements are singled out and calibration is performed by key data corresponding to version 5.01 and 5.04, the Pre-Processing step yields to the determination of the measured spectral reflectance at the aerosol working wavelengths, λ_a, for the selected ground pixels useful for the aerosol retrieval. Pixels whose spectra exhibit sun-glint behaviour are rejected. Furthermore, polar regions which are characterized by high surface albedo – latitudes > 70°- and pixels with solar zenith angle > 70° are also avoided, so that the plane parallel atmosphere approximation can be assumed.

FRESCO (Fast Retrieval Scheme for Cloud Observables) [12] algorithm's products, freely available via ESA-DUP-TEMIS project (www.temis.nl), are adopted to identify clouds' presence over the ground pixel. Only calibrated SCIAMACHY data presenting effective cloud fraction values lower than 0.05 are considered in this retrieval approach.

Afterwards, six wavelengths in the channels 2 (309-405 nm), 3 (394-620 nm) and 4 (604-805 nm) of SCIAMACHY are properly selected in spectral regions having very weak gaseous absorption features i.e.: atmospheric trace gases transmittances are greater than 99.7%. Another criterion used for wavelengths selection concerns the spectral distance between two nearest wavelengths that must be at least 20 nm. In this way, the exploitation of several wavelengths in the whole SCIAMACHY spectrum becomes more effective to distinguish different types of aerosol. In Table 1 are listed the selected aerosol working wavelengths, λ_a. Actually $\lambda_a < 700$ nm are employed both over ocean and land while $\lambda_a > 700$ nm are employed in case of ocean pixels only. At the selected wavelengths, TOA reflectances are calculated as $R_{exp}(\mu_0,\mu,\phi)=\pi I(\mu_0,\mu,\phi)/\mu_0/F_0$, where μ_0 is the cosine of the solar zenith angle at TOA, μ is the cosine of the observing angle, and ϕ is the relative azimuth angle for each ground pixel.

Once measured reflectances are properly corrected for the systematic SCIAMACHY underestimation, as it will be carefully described in the next section, the Processing phase can start. Here, simulated reflectances $R_{mod}(\lambda_a)$ are calculated in the same geophysical conditions of the pixel in analysis using the DOWNSTREAM radiative transfer model (RTM) [13]. In the present model the atmosphere is considered to be cloudless, horizontally homogeneous and vertically divided into three layers: a uniform mixture of aerosol and molecules between two pure molecular layers, bounded by a lambertian reflecting surface.

In our retrieval approach a set of eight aerosol classes were selected to describe the interaction between aerosol and solar radiation Among these, five are literature models: Maritime, Desertic, Maritime Polluted, Clean Continental and Rural [14, 15] and should be regarded as optically equivalent aerosol types mimicking the realistic aerosols. Beside these, three aerosol classes were introduced to describe particles originating from biomass burnings (Biomass Burning class), remote and pristine marine environment conditions (Maritime-Lanai class) and urban pollution (Urban class). AOP for these models were calculated [16] starting from microphysical properties, refractive index and size distribution, derived from ground based measurements in African Savanna, Lanai Island and Paris-Creteil, respectively [17].

The global database of monthly Minimum Lambert-Equivalent Reflectivity (MLER) [18] derived from 5 years of GOME observations in the 335-772 nm spectral range is chosen to estimate the surface contribution TOA reflectance.

In order to take in to account actual ground level in the retrieval, a Digital Elevation Model (DEM) has been inserted in ASP. The selected DEM is the GTOPO30, which has been prepared by the U.S. Geological Surveys.

Table 1. SCIAMACHY reflectance correction factors and associated errors used in ASP for aerosol working wavelengths.

ASP λ_a (nm)	C_{sl}	Δ_{sl}	C_{off}	Δ_{off}
364	1.158	0.028	-	-
387	1.143	0.042	-	-
429	1.130	0.040	-0.01	0.0100
683	1.157	0.020	-0.01	0.0080
754	1.187	0.022	-0.01	0.0082
775	1.191	0.023	-0.01	0.0084

Summarizing, given a set of SCIAMACHY reflectance $R_{scia}(\lambda)$, with their own measurement errors σ_{scia}, they are fitted by means of the Levenberg-Marquardt least squares method (LMFM) to modeled reflectance $R_{mod}(\lambda_a)$ to achieve a minimum in the Chi-Square merit function defined as:

$$\chi^2(\tau_a)=\sum_{i=1}^{N}\left(\frac{R_{scia}(\lambda_i)-R_{mod}(\lambda_i,\tau_a,\text{Class})}{\sigma_{scia}(\lambda_i)}\right)^2. \quad (1)$$

The LMFM is independently applied for each of the aerosol classes. These fitting procedures produce, as output, the best-fit parameter AOD and the corresponding χ^2, called the residual of the fittings for each aerosol class. The smaller fitting residual among the available values is selected: the corresponding couple formed by the parameters AOD at 500 nm wavelength and class are the resulting aerosol characteristic of the pixel being analysed.

The last part of ASP, Post-processing, is focused on the quality check by means of the assessment of χ^2 values and a Discrimination Index (DI) on the aerosol class previously retrieved. DI has been defined as ratio between the χ^2 related to one aerosol model and the χ^2 related to the winner and it is calculated at the end of the retrieval processing. A statistical analysis suggested to consider DI ≥ 4 to consider the aerosol class as distinguishable. At the end of the processing chain, pixels collocated in space and time with ground-based AOD measurements are selected to allow comparison and validation of the satellite aerosol retrieval.

3 REFLECTANCE CORRECTION FOR AEROSOL OPTICAL DEPTH RETRIEVAL

SCIAMACHY underestimates the reflectance in the UV and VIS-NIR range by about 10 to 25% and 10 to 20%, respectively [7, 6]. Employing Level 1B data without a proper reflectance correction leads to meaningless aerosol retrieval. In the following data analysis the measured TOA reflectances are corrected taking into account the works by [7] and [6] for the UV and VIS-NIR range, respectively. Tilstra et al. [7] derived spectral correction factors in the range 240-400 nm by comparing SCIAMACHY spectral reflectance and DAK (Doubling-Adding KNMI RTM) simulated reflectance over different surfaces (Sahara, ocean, and vegetation). Under the hypothesis of a linear relation between SCIAMACHY and MERIS reflectances, Acarreta et al. [6] provided a set of correction factors at wavelengths 442, 510, 665, 708, and 885 nm taking account different underlying surfaces (desert, vegetation land, and ocean).

In the ASP data processing, measured spectral reflectance, R_{scia}, are corrected using the linear relationship: $R_{scia\text{-}corr}(\lambda_a) = C_{sl}(\lambda_a) \times R_{scia}(\lambda_a) + C_{off}(\lambda_a)$, where C_{sl} and C_{off} are the interpolated values at λ_a of the correction factors derived from [6] and [7] and related to ocean and vegetation surfaces. Table 1 summarizes the interpolated TOA reflectance correction factors, C_{sl} and C_{off} and their associated uncertainties, Δ_{sl} and Δ_{off}. In particular, these last quantities contribute to the total error, $\sigma_{scia\text{-}corr}(\lambda_a)$, employed in the χ^2 function of Eq.1.

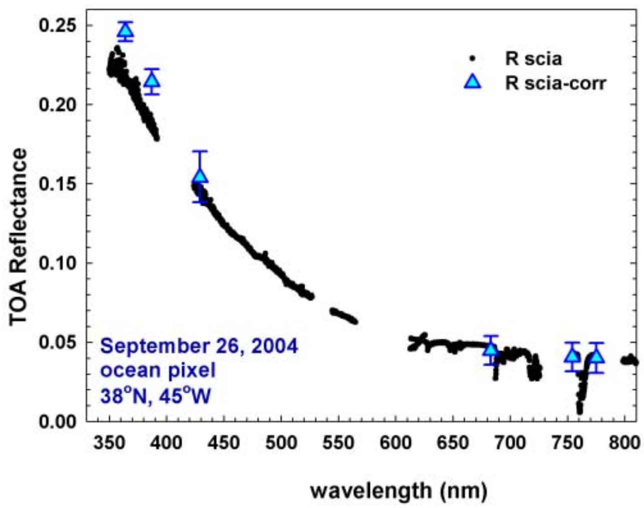

Fig.1. Spectral reflectance as measured by SCIAMACHY R_{scia} (black dots) and corrected reflectance values $R_{scia\text{-}corr}$ for an ocean pixel. Error bars in $R_{scia\text{-}corr}$ are due to the minimum and maximum values of the correction coefficients.

In Fig.1 an example of this correction is reported applied to oceanic pixel. It can be observed that in the UV spectral range the minimum reflectance correction, represented by the lower limit of the error bar, has higher values respect to the measured reflectance, while in the NIR the adopted correction doesn't introduce a significant variation in the reflectance values. This can be due to a non linear effect recognized by [6] for low reflectance domain in the

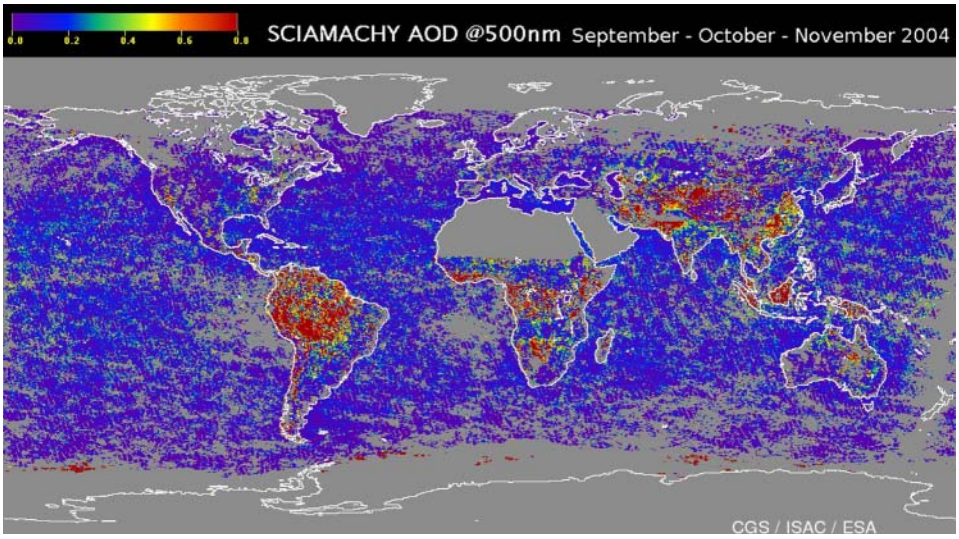

Fig.2. Mean AOD @ 500 nm for September, October and November 2004 as retrieved by ASP from SCIAMACHY nadir measurements.

SCIAMACHY - MERIS comparison aimed at the determination of the correction coefficients.
AOD at 500 nm were retrieved applying the above correction procedure for September, October, and November 2004. Average values for the whole fall season were calculated and showed in Fig.2. This global map displays a relatively low aerosol loading over oceanic areas, with AOD < 0.2, while hot spots in AOD, presenting values ≥ 0.5, can be clearly identified in South America, South Africa, North of India, East China and Indonesia.
In order to assess the effect in the aerosol retrieval due to the error associated to the reflectance correction factors only, the retrieval is carried out also using measured reflectance corrected at first by the maximum values for the correction coefficients, $C_{sl\text{-}max} = C_{sl} + \Delta_{sl}$ and $C_{off\text{-}max} = C_{off} + \Delta_{off}$, and then by the minimum values, $C_{sl\text{-}min} = C_{sl} - \Delta_{sl}$ and $C_{off\text{-}min} = C_{off} - \Delta_{off}$.
Results relative to these different retrievals for one day of SCIAMACHY data are synthesized in the scatter-plots of Figure 3. Here AOD retrieved using the correction couple (C_{sl}, C_{off}) for measured TOA reflectances are compared first to AOD retrieved using ($C_{sl\text{-}min}$, $C_{off\text{-}min}$) (Fig. 2a) and then to AOD retrieved using ($C_{sl\text{-}max}$, $C_{off\text{-}max}$) (Fig. 2b).
As expected, AOD($C_{sl\text{-}min}$, $C_{off\text{-}min}$) retrieved in the first case and AOD($C_{sl\text{-}max}$, $C_{off\text{-}max}$) relative to the second case are typically lower than and greater than AOD(C_{sl}, C_{off}), respectively.

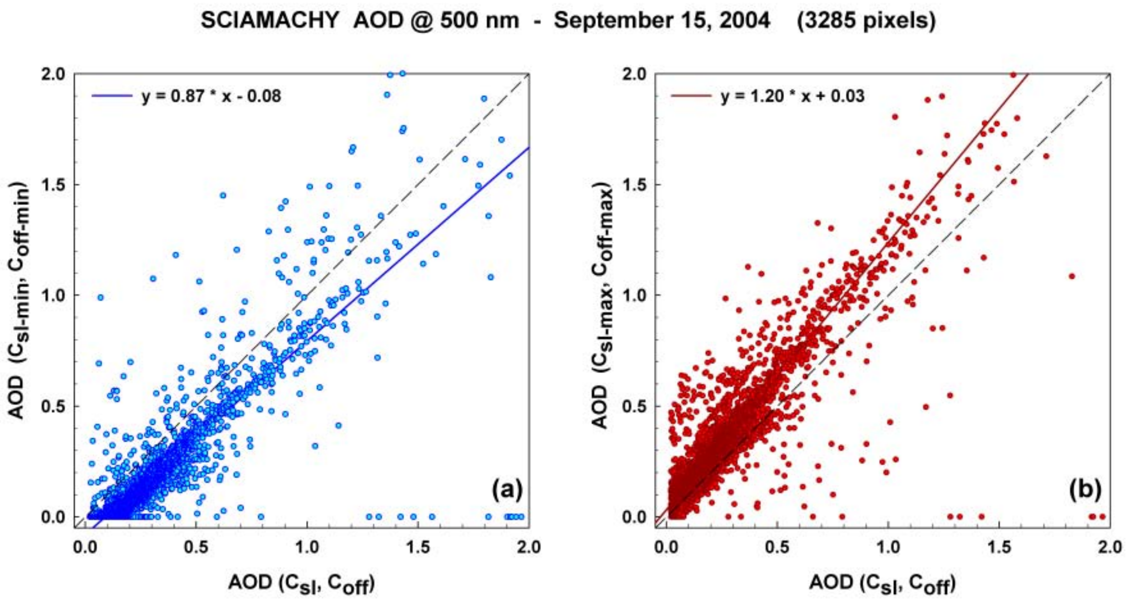

Fig.3. ASP AOD retrieved for September 15, 2004 using reflectance correction factors (C_{sl}, C_{off}) compared to (a) those retrieved using ($C_{sl\text{-}min}$, $C_{off\text{-}min}$), and (b) those retrieved using ($C_{sl\text{-}max}$, $C_{off\text{-}max}$), along with the relative linear regressions.

The linear regression calculated for each plot permits to estimate the propagated uncertainty in the AOD retrieved from SCIAMACHY as $\Delta\,\mathrm{AOD} = \pm\begin{pmatrix} 0.03 + 0.20\,\mathrm{AOD} \\ 0.08 + 0.13\,\mathrm{AOD} \end{pmatrix}$. In particular, the uncertainty related to the reflectance correction makes AOD varying of more than 0.1 in the 51% and more than 0.2 in the 11% of the overall pixel analysed. Moreover, if AOD varies by at least 0.1 (0.2), the retrieved aerosol class turns out to change in 18% (5%) of the cases. Being ASP retrieval algorithm based on a multispectral analysis, these variations in the retrieved aerosol class are due to the wavelength's dependence of the errors associated to the correction factors.

4 COMPARISON WITH AERONET MEASUREMENTS

This section reports the comparison between AOD@500 nm observations at nine AERONET land and ocean sites, and collocated ASP AOD retrieved using SCIAMACHY reflectance corrected by means of the factors (C_{sl}, C_{off}) presented in Table 1.

Corresponding data are related to 2003 and 2004. Among AERONET ground stations, three are located in South America (Alta Floresta, Cuiaba Miranda, and Rio Branco), two in Europe (Lille and Leipzig), three in Atlantic Ocean islands (Ascension Island, Azores and Cape Verde) and one in South Africa (Mongu), to test ASP processor for different aerosol loading conditions like maritime, desert dust outbreaks, biomass burning and urban pollution. AERONET AOD Level 2 data (i.e.: cloudy screened and quality assured), freely provided via http://aeronet.gsfc.nasa.gov/, were employed for this comparison. It has been required that AERONET measurements are within ± 30 min respect to SCIAMACHY overpasses. Results of this comparison are shown in the scatter plot of Fig. 4 where ASP and AERONET AOD present a general good agreement. A tendency of ASP in underestimating AOD values can be recognized. The 1σ uncertainty on ASP retrieval can be estimated as $\Delta\mathrm{AOD} = \pm\, 0.03 \pm 0.06\mathrm{AOD}$.

Different agreements in the comparison for land and ocean sites can be pointed out. In the land sites case, the linear regression provides values equal to 0.07 for the offset and 0.85 for the slope, with a regression coefficient of 0.93. For the island sites, offset is found to be equal to 0.13 and slope to 0.24, with regression coefficient of 0.38. Combined effects due to the reflectance correction and surface reflectance employed in the retrieval can explain these different behaviours. Actually, over ocean and for cloud free conditions, the surface contribution to the TOA signal in the UV-VIS-NIR is typically very weak. As reported in Section 3, in comparing MERIS and SCIAMACHY spectra for reflectance lower than 0.2, non-linearity effects have been emphasized in [6]. Then, the derived spectral reflectance correction factors can introduce a systematic error when applied in the correction of small TOA reflectance, resulting in a bias in the AOD estimates.

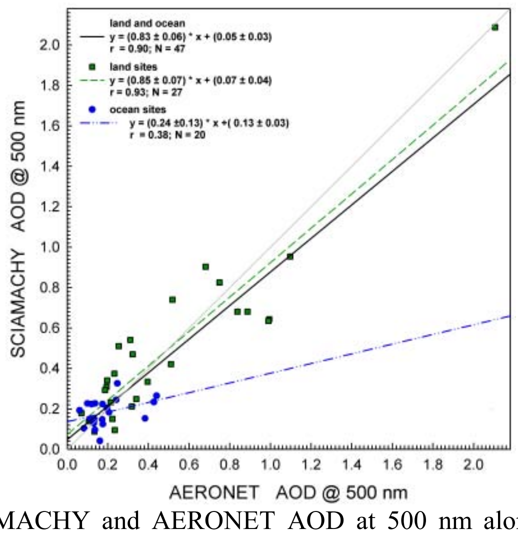

Fig.4. Comparison between SCIAMACHY and AERONET AOD at 500 nm along with linear best fit. Spatial and temporal coincidences, referring to 2003 and 2004, are singled out for ocean and land sites.

5 CONCLUSIONS

Taking into account the known underestimation in SCIAMACHY reflectance, we explored the possibility to analyse SCIAMACHY data in order to obtain reliable information on the tropospheric aerosols loading. A reflectance correction

procedure of the SCIAMACHY measurements was applied in the ASP retrieval on the basis of the observations presented by [6] and [7].
A global map of mean AOD at 500 nm, relative to September, October, and November 2004, obtained with the described retrieval approach, displays a relatively low aerosol loading over oceanic regions, with AOD < 0.2, while hot spots in AOD, presenting values ≥ 0.5, can be clearly identified in different land areas.
To test the reliability of our retrieval approach, ASP AOD were set against corresponding AERONET measurements resulting in a good agreement (r = 0.93) in the case of significant aerosol loading over land and a minor agreement (r = 0.38) for the retrieval over ocean. Comparison with AERONET also provides a 1σ uncertainty on ASP retrieval evaluated as ΔAOD = ± 0.03 ± 0.06AOD.
On the other hand, uncertainties in the reflectance correction factors lead to a significant propagated error in the retrieved AOD of the order of ± 20% for AOD around 1 and up to 90% for AOD about 0.1.
Then, this preliminary reflectance correction applied herein encourages the adoption of SCIAMACHY sensor for aerosol loading detection and estimation and at the same time strengthens the need to use an official re-calibrated version of Level 1B data in order to improve the consistency of low reflectance measurements and then increase the accuracy degree of the aerosol retrieval.

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